AD-A282 489

A RAND NOTE

Air Combat Model Engagement and Attrition Processes High Level Design

Patrick D. Allen

RAND

The research described in this report was sponsored jointly by the United States Air Force under Contract F49620-91-C-0003 and the United States Army under Contract MDA903-91-C-0006.

Published 1993 by RAND
1700 Main Street, P.O. Box 2138, Santa Monica, CA 90407-2138
To obtain information about RAND studies or to order documents,
call Distribution Services, (310) 393-0411, extension 6686

A RAND NOTE

N-3566-AF/A

Air Combat Model Engagement and Attrition Processes High Level Design

Patrick D. Allen

Prepared for the
United States Air Force
United States Army

RAND

PREFACE

This Note describes the high-level design of air combat engagement and attrition processes in the theater-level combat or nonlinear combat (TLC/NLC) model, and possibly for the RAND Strategy Assessment System (RSAS). This document should be of interest to individuals responsible for designing and using air combat models.

The project was sponsored jointly by the U.S. Air Force Studies and Analysis Agency and the U.S. Army Concepts Analysis Agency. It was conducted jointly under the Force Employment Program of Project AIR FORCE, and by the Army Research Division's Arroyo Center. Project AIR FORCE and the Arroyo Center are two of RAND's federally funded research and development centers.

SUMMARY

PURPOSE

The purpose of this high-level design *document* is to act as a basis of discussion between model designers, model users, and the sponsors. The purpose of the model *design* is to allow applications to many implementations, especially as part of an overall hierarchy of models.[1] The purpose of the *types of models* in which this design is implemented, such as the theater-level combat or nonlinear combat model (TLC/NLC) or possibly the RAND Strategy Assessment System (RSAS), is to support policy-level analysis of air combat issues primarily at RAND, but possibly at other institutions as well.[2]

Although the document has been reviewed within RAND and by various Air Force agencies, it is not considered final, but continues to act as a point of discussion within the community. The primary question we are asking at this stage is whether or not we have left out any major issue of air combat. To that end, any questions or suggestions about this Note should be directed to the author or the TLC/NLC model designer, Richard Hillestad.[3]

OBJECTIVES

The objectives of this *document* are to describe the high-level design of an air combat engagement and attrition model, present the design to potential RAND study

---

[1]The goal is to create a design for an air combat model at the theater level, more or less independent of the software models in which the design is actually implemented. A number of these design features have already been implemented in the TLC/NLC model and some may also be implemented in the RSAS. (See the bibliography for other documents describing the TLC/NLC model and the background behind the current model design.)

[2]"The TLC/NLC modeling tool kit is a prototype for a combat simulation model being developed in a research effort at RAND to improve air and land combat simulation at the operational and theater level.... The impact of dramatic changes in the political-military environment, the need to treat more explicitly the large uncertainties present in today's analytic environment, and an opportunity to capitalize on new methodological, software, and hardware developments have all provided an impetus to the research on TLC/NLC. The major design goals for the model include the capability for analyst operation via an intuitive graphical user interface, facilities for incorporating input from database management systems, tools for managing multiple simulation runs and other application software for further analysis and display." From Hillestad et al., forthcoming, pp. iii and xiii.

[3]Both can be reached at (310) 393-0411 x6818 or x7888, RAND, P.O. Box 2138, Santa Monica, CA 90407-2138.

sponsors to ensure that the key factors of air combat are addressed, and to publish this updated version as a point of reference during model implementation and evaluation.

The objectives of the model *design* are to include many of the more qualitative factors not traditionally included in previous air combat models. For example, the model includes features such as the effects of navigational aids in helping aircraft reach their targets, or the effects of intelligence on the frequency and distribution of specific types of air-to-air, ground-to-air, and air-to-ground engagements.

The design defined in this document addresses primarily how many aircraft or SAMs of each type destroy each other in a given engagement assessment process. Although the factors that contribute to the actual assessment and the combatants have been specified, the definition of the assessment process itself has not been defined in too much detail. This lack of detail is intentional, and will allow us to calibrate this air combat assessment model to higher-resolution air combat models, such as Tac Brawler, RJARS, and other higher resolution models. The exact calibration process is reserved for the next phase of documentation, and is more appropriate for a detailed design document.

One main objective is to not revise this design significantly over time, so that many different implementations of the model may be based on this original design. The discussion presents the factors that need to be addressed by an air combat model, where and when in the model these factors need to be addressed, and how the model is organized to facilitate comparisons between different versions of the model. For example, one implementation of this design may be deterministic, while another may be stochastic. The ability to readily compare the outputs of both the deterministic and stochastic implementations of the model is a specific model design goal.

APPROACH

The model design is intended to be either stochastic or deterministic, with either low resolution or high resolution, depending upon the needs of the user. A key feature is to design the model so that the outputs of each version will be readily comparable given similar inputs. This goal is achieved when the following three features are included: First, the key factors of each part of the model may be used as labels for inputs from higher-resolution models, or as parameters in more aggregate assessment algorithms. Second, each situation being assessed must be explicitly

defined. Third, care must be taken in defining which variables are stochastic and which variables are deterministic.

Factors as Labels or as Parameters

One advantage of this design lies in the realm of model calibration. One could implement this design in a model where each factor is represented by a model parameter. As an alternative, one could implement the model that refers to higher-resolution model outcomes. In the latter case, the list of factors in the design are used as *labels* so that the most appropriate higher-resolution outcome may be applied. Wherever there are factors in the design not represented by the higher-resolution models, then those factors must still be represented as explicit model parameters.

Explicitly Define the Situations

Explicitly defining the situations for assessment makes the comparison between different versions of the model relatively easy. The cases or algorithms used to represent the results of engagements must be sufficiently robust to account for the range of results that could be expected in the assessment processes. If the situations are too broadly defined, then the assessment process employed may not apply to all cases. For example, when small numbers of assets are engaged, the law of large numbers may not apply, and therefore the central limit theorem does not apply, and therefore the deterministic representation will not match the mode or mean of the stochastic distribution of results.

Define Variables That Are Linearly Divisible over Time

The second feature is to select the key model variables so that they are comparable in both the deterministic and stochastic versions of the model. Since probabilities carry with them an associated rate for a specific event, any division of that event will not readily produce the same results of the original event. However, if one selects variables that are linearly divisible over time, then the deterministic and stochastic versions of the models are readily comparable. For example, the attrition rate of aircraft in a ground-to-air engagement zone is not linearly divisible over time, while the number of engagements in the ground-to-air engagement zone is linearly divisible over time.

Defining the Outputs First

Another feature of this model design is the emphasis on "outputs first." In this approach, the outputs of a given assessment process are defined first, and then the factors necessary to calculate that output are defined second. The process of calculating the outputs may become more elaborate as user needs and data availability increase. This approach is key to successful variable resolution modeling, and was originally applied to the S-Land model in the RSAS (Allen and Wilson, 1987).

OVERALL AIR COMBAT ASSESSMENT PROCESS

The air combat assessment model is assumed to begin when the penetrating aircraft leave their airbases and begin their journey into enemy territory. There are three main parts to the overall assessment process:

- Determine whether or not penetrators are detected before reaching the engagement zones,
- Determine the sequence of ground-to-air, air-to-air, and air-to-ground engagements, and
- Assess air-to-air, ground-to-air, and air-to-ground engagements in sequence determined for ingress and egress.

AIR-TO-AIR ENGAGEMENTS

Air-to-air engagements are assessed in rounds. Each round includes:

- The determination of the number of interceptors that intercept the penetrators,
- The determination of the number of escorts, sweep aircraft, or bombers that engage interceptors, and
- The results of each round of air-to-air engagement.

The key output of the first step is the probability that the penetrators are intercepted by interceptors, using an allocation rule as an upper bound. The output of the second step is the probability the interceptors are engaged by escorts, sweep aircraft, or bombers (again, with an upper bound based on allocation rules that are based on each side's perceptions). The outputs of the engagement are the number of

penetrators and interceptors destroyed, the expenditures on each side, and the number of aircraft on each side that can continue their mission.

GROUND-TO-AIR ENGAGEMENTS

Ground-to-air engagements include the following steps:

- The determination of the number of SAM and AAA engagements against the penetrators,
- The determination of the number of SEAD engagements against SAMs and AAA,
- The results of the SEAD engagements against the SAMs and AAA, and
- The results of each round of the SAM and AAA engagements against the penetrators.

The output of the first step is the probability that the penetrators could be engaged by SAMs and AAA (with an upper bound on allocation based on perceptions). The output of the second step is the probability that the penetrator SEAD assets could engage the SAMs and AAA (with an upper bound on allocation). The outputs of the third step are the number of SAMs and AAA destroyed, the number suppressed, and the expenditures of SEAD munitions. The outputs of the last step are the number of penetrators destroyed, the number aborted, and the expenditure of SAM and AAA munitions.

AIR-TO-GROUND ENGAGEMENTS

Air-to-ground engagements include the following steps against either primary or secondary targets:

- The determination of the number of penetrators that arrive at the target,
- The determination of the results of the terminal defense engagements,
- The determination of the penetrator acquisition of the target,
- The assessment of the damage against the target, and
- The BDA assessed by the penetrators.

The output of the first step is the probability that the aircraft arrive at the target location. The outputs of the second step are the same as the ground-to-air

engagements described above. The output of the third step is the probability that aircraft acquire their targets. The outputs of the fourth step are the munitions expended, the damage to the target, and any collateral damage. The output of the last step is the information (BDA) collected on both the damage to the target and the collateral damage.

The appendix presents more detail on the design of engagement zones in the TLC/NLC model.

ACKNOWLEDGMENTS

Many RAND colleagues contributed to this design document. Richard Hillestad and Louis Moore created and implemented the original engagement zones in the TLC/NLC model. In addition, the following contributed specific points that were included in the updated design: Bart Bennett, Donald Emerson, Daniel Fox, David Frelinger, Edward Harshberger, Robert Howe, Theodore Parker, William Stanley, and Donald Stevens. Special thanks goes to Bruce Davis who performed the formal RAND review of this document, and to RAND editor Patricia Bedrosian.

Comments from the following external reviewers were included in this document: Colonel Michael W. Schoenfeld, Director, Advanced Programs ACC/DRB; Allen Murashige, AFSAA/SAG; Colonel Coy Fink, Vice Commander, Fighter Weapons School, 57th Fighter Wing (ACC); Frank Campanile, ASD/XRM; David Orletsky, AF/XOOC; and Major Roy Y. Sikes, AF/XOOC.

Any remaining errors or omissions are the fault of the author.

CONTENTS

FIGURES

GLOSSARY

AAA	Anti-Aircraft artillery
ACC	Air Combat Command
AI	Air Interdiction (mission)
AWACS	Airborne Warning and Control System
AWSIM	Air War Simulation
BAI	Battlefield Air Interdiction (mission)
BDA	Bomb Damage Assessment
BVR	Beyond Visual Range
C3I	Command, Control, Communications, and Intelligence
CAP	Combat Air Patrol
CAS	Close Air Support (mission)
DCA	Defensive Counter Air (mission)
ECM	Electronic Countermeasure
EMCON	Emissions Control Level
FAC	Forward Air Controller
GCI	Ground Controlled Intercept
GPSS	Global Positioning Satellite System
HLD	High-Level design
LANTIRN	Low-Altitude Night-Targeting Infrared Navigation
OCA	Offensive Counter Air (mission)
OPVIEW	Operational Value of Intelligence and Electronic Warfare Model
RJARS	RAND's Jamming and Radar Simulation
RSAS	RAND Strategy Assessment System
SAM	Surface-to-Air Missile
SEAD	Suppression of Enemy Air Defenses
Tac Brawler	Tactical aircraft engagement model
TAC Thunder	Air combat model
TLC/NLC	Theater-Level Combat or Nonlinear Combat Model

1. INTRODUCTION

PURPOSE

The purpose of this *document* is to act as a common basis of discussion between air-ground combat model designers, model users, and the sponsors. The purpose of the model *design* is to allow applications to many implementations, especially as part of an overall hierarchy of air-land combat models.[4] The purpose of the *types of models* in which the design is implemented, such as the theater-level combat or nonlinear combat model (TLC/NLC)[5] and the RAND Strategy Assessment System (RSAS), is to support policy-level analysis of air combat issues primarily at RAND, but possibly at other institutions as well.[6]

OBJECTIVES

This *document* describes an overall, or high-level, design of an air combat engagement and attrition model; provides the design to potential RAND study sponsors to ensure that the key factors of air combat engagement and attrition are addressed; and provides the updated version as a point of reference during model implementation and evaluation. These first two objectives have been accomplished and the third is under way.

---

[4]The goal is to create a design for an air combat model at the theater level, more or less independent of the software models in which the design is actually implemented. A number of these design features have already been implemented in the TLC/NLC model and some may also be implemented in the RSAS in the future. (See the bibliography for other documents describing the TLC/NLC model and the background behind the current model design.)

[5]"The TLC/NLC modeling tool kit is a prototype for a combat simulation model being developed in a research effort at RAND to improve air and land combat simulation at the operational and theater level.... The impact of dramatic changes in the political-military environment, the need to treat more explicitly the large uncertainties present in today's analytic environment, and an opportunity to capitalize on new methodological, software, and hardware developments have all provided an impetus to the research on TLC/NLC. The major design goals for the model include the capability for analyst operation via an intuitive graphical user interface, facilities for incorporating input from database management systems, tools for managing multiple simulation runs and other application software for further analysis and display." From Hillestad et al., forthcoming, pp. iii and xiii.

[6]The RAND combat models of this type are designed to perform policy-level analysis, having to do with such topics as force structure, concept development, net assessments, or the aggregate effects of selected assets. These are not primarily training models, although they have been used in selected training exercises. These types of models are not test and evaluation tools per se.

The objectives of the model *design* are to include many of the more qualitative factors not traditionally included in previous aggregate-level air combat models, such as the effects of navigational aids in helping aircraft reach their targets, or the effects of intelligence on the frequency and distribution of specific types of air-to-air, ground-to-air, and air-to-ground engagements. Since this is a high-level design document, the details of the actual model's implementation will not be included here except as examples. For example, the design refers to decision rules for target prioritization and resource allocation. Since the priority and allocation rules change much more quickly from implementation to implementation than do the attrition-assessment algorithms, specific allocation rules are not included here. This design document is intended to remain relatively unchanged, focusing on the factors that matter in air combat and the sequence in which events are assessed, rather than on the details of specific model implementations of this design.

Many different implementations may be associated with this design, each varying both by model and over time, as the details, algorithms, or approaches to assessing specific situations evolve. For example, the scheme used to allocate aircraft may vary by region, nationality, type aircraft, mission, or analysis issue. The need to have an allocation scheme, where it lies in the sequence, and the factors it should consider are not likely to change, whereas a specific allocation scheme is likely to change rather radically. Similarly, the mission abort criteria may vary over a wide variety of cases, but the need to represent a mission abort and where in the sequence to assess that event are not likely to change.

What is presented is the list of factors that need to be addressed by an air combat model, where and when in the model they need to be addressed, and how the model is organized to facilitate the types of comparisons described above. One implementation of this design may be deterministic, while another may be stochastic. It is hoped that this document will not change radically over time or as a function of the implementation, but that the main features of air combat assessment will remain relatively constant.

APPROACH

The model design is intended to be either stochastic or deterministic, with low resolution or high resolution, depending upon the needs of the user. These four combinations of the model will be referred to as "versions" of the model throughout the text.

A key feature is to design the model so that the outputs of each version of the model will be readily comparable given similar inputs. Such a goal is achieved only when care is taken in defining three key design features. First, the factors listed in the model design should be capable of being used as labels for higher-resolution model outputs, or as parameters in more aggregate algorithms. Second, the explicit situations being assessed must be carefully defined so that the space of situations is covered, and there is minimum ambiguity between situations being assessed. Third, the model designer must carefully define which variables are stochastic and which variables are deterministic with an eye to keeping their results readily comparable.

Factors as Labels or as Parameters

One advantage of this design lies in the realm of model calibration. All models need to have their parameters set based upon some criteria. For one study, one may wish to explicitly represent all of the factors listed in the document as model parameters. In other studies, one may wish to calibrate the model's parameters to a higher-resolution model, such as one that explicitly models the details of a few-on-few air-to-air engagement. This document describes a design that is useful for either type of calibration.

In the case of explicit modeling, the factors listed will need to be addressed by some factor or algorithm. In the case of calibrating to a higher-resolution air combat model, the factors can be used to ensure that the right calibration case is being used. For example, if the calibration air-to-air engagement is two interceptors against two escorts and two bombers, the higher-resolution model had some assumptions about all of the factors listed in this document. For those factors the higher-resolution model explicitly represented, the *label* of the calibration case must include the value assumed or represented in the model for those factors. If the higher-resolution model did not address all of the relevant factors, then the model in which this design has been implemented needs to include an explicit representation of those factors not addressed by the higher-resolution model.

In this design document, it was assumed that results from higher-resolution models would be available for calibration, and that some scheme for labeling these cases would be required. The factors listed in this document should also be included in the labeling scheme for the higher-resolution model cases. Overall, the calibration of the inputs of one model to the outputs of another model as part of a hierarchy of

models is not an easy task. However, specifically defining the labels associated with each model run will ease the calibration process between models in such a hierarchy.

Explicitly Define the Situations

Explicitly defining the situations for assessment makes the comparison between different versions of the model relatively easy. For example, assume that one defines that engagement types are not a function of the number of aircraft of each side involved in the engagement. The cases or algorithms used to represent the results of these engagements may not be sufficiently robust to account for the wide range of results that could be expected in few-on-few and many-on-many engagements.

For example, a stochastic representation of a many-on-many engagement may be readily compared to a deterministic representation of the same event and may produce comparable results. Since the central limit theorem may apply in the many-on-many case, the average result may be closely related to the mean or mode of the stochastic distribution. However, if one attempts to compare the results of a few-on-many engagement using the average or mean result, the results may not be comparable. Since the central limit theorem is not likely to apply when few assets are involved on one side, one must more carefully define the situation to handle the factors that cause the central limit theorem to not apply.

Therefore, one key feature in designing a model that may be either deterministic or stochastic is to clearly define the situations being assessed, ensuring that distinctly different cases are assessed differently.

Define Variables That Are Linearly Divisible over Time

The third feature is to design the key model variables so that they are comparable in both the deterministic and stochastic versions of the model. If one selects the wrong variables, the results of the stochastic version are not readily comparable to those in the deterministic version. For example, presume that 100 penetrating aircraft are assessed to lose 15 aircraft to ground-based air defenses. The model may also specify that an air-to-air engagement occurs two-thirds of the way during the passage across the ground-to-air engagement zone. If one were to simply assume that two-thirds of the attrition occurred before the air-to-air engagement, and one-third after, then the same results would not occur when there was no air-to-air engagement.

To elaborate, a 10 percent ground-to-air attrition rate (two-thirds of the 15 percent for the whole ground-to-air engagement) is assessed against the 100 aircraft, resulting in 10 aircraft shot down and 90 penetrating aircraft remaining before the air-to-air engagement. Assume for a moment that no penetrators are lost during the air-to-air engagement. The second part of the ground-to-air engagement is then assessed at 5 percent (one-third of the initial 15 percent). As a result, a 5 percent attrition rate against the remaining 90 aircraft results in an average 4.5 additional aircraft lost. A total of 14.5 aircraft were lost if the air-to-air engagement occurred (even with no air-to-air losses), but 15 aircraft would have been lost if no air-to-air engagement occurred. Therefore, it would be difficult to compare stochastic and deterministic versions of this model since the variable "percent attrition due to ground-to-air" is not readily divisible over time.

As an alternative, one could design the model around the variable "number of engagements of penetrating aircraft by ground-to-air defenses." In this case, let us assume that there were 30 missile firings against the 100 aircraft resulting in 15 penetrating aircraft shot down. The probability that a given missile engagement destroyed an aircraft is 50 percent. To assess the 30 missile engagements, assume 20 (two-thirds) occurred before the air-to-air engagement, and 10 occurred after. The first 20 missile engagements result in 10 aircraft destroyed (0.5 kills per missile firing). There are 90 aircraft remaining. After the air-to-air engagement has been assessed (with no additional losses to the penetrators as in the preceding example), the remaining 10 missile engagements are assessed. Another 5 aircraft are shot down due to the 50 percent kill rate per engagement. As a result, the same number of penetrating aircraft are destroyed whether or not an air-to-air engagement was assessed.

The key to designing a model with readily comparable deterministic and stochastic versions is to use variables that are linearly divisible over time. A given probability (such as 15 percent attrition to the flight due to ground-to-air assets) has an implicit rate over time associated with an event. Any change in the definition of the event, such as dividing it over time, results in a nonlinear effect on the rate or probability. One cannot assess part of the event now and then the rest of the event later, since the event does not divide linearly over time, as shown in the first example. However, if one focuses on variables that are linearly divisible over time, such as the number of engagements, then the probabilities associated with each engagement event may be assessed separately for each engagement. The result is

that the deterministic and stochastic versions of the model can be more readily compared when using variables that divide linearly over time.

In the two preceding examples, if the air-to-air attrition rate was so severe as to cause 50 of the remaining 90 aircraft to be destroyed, then the second ground-to-air engagement may be distinctly different. If the penetrators do not abort the mission, then the number of ground-to-air engagements may no longer be 10 ground-to-air missile engagements assessed against the penetrators after the air-to-air engagement, but possibly a smaller number of ground-to-air missile engagements. For this reason it is important to explicitly define what constitutes a specific type of assessment process. Conversely, if the ground-based air defenses were already swamped, then the number of engagements may not change because the maximum number of engagements allowed has already been reached.

Designing the model so that the outputs of different versions are comparable allows the *causes* behind the outputs to also be readily comparable. The use of the same key variables as the basis for both the low-resolution and high-resolution versions of the model will facilitate this comparison of results. Without the use of selected key variables that mean the same thing in each model, there would be little opportunity to calibrate results that could be readily traced to the cause in each model. For example, if both models have a variable called the "probability of engagement of penetrators by interceptors," then the cause of attrition to the penetrators by the interceptors can be readily traced and compared in both models. Exactly how that probability is defined may be a function of a large number of other variables in the high-resolution model, and may be defined by fiat in the low-resolution model, but the basic design structure lends itself to easy comparison for purposes of cause tracing (Allen, 1992).

These two prime objectives of ensuring comparable and traceable results between high- and low-resolution versions, and between stochastic and deterministic versions of the model, will be apparent as the details of the model design are described below.

ORGANIZATION OF THE DOCUMENT

The next section presents an overview of the air combat assessment process. Sections 3 through 5 present the air-to-air, ground-to-air, and air-to-ground assessment processes, respectively. Section 6 presents some final comments about

the model design, and the appendix discusses four geometric calculations associated with the more detailed TLC/NLC model representation.

2. OVERALL AIR COMBAT ASSESSMENT PROCESS

The air combat assessment model is assumed to begin when the penetrating aircraft leave their airbases and begin their route into enemy territory. (This document does not address the command and control and planning of air operations or the creation of the air tasking order, just the in-theater combat assessment part.) There are three main parts to the overall assessment process, as shown in Figure 2.1.

The first part determines whether or not the penetrators are detected before reaching the first engagement zone. For example, some types of long-range sensors can detect the takeoff and marshalling of aircraft at the enemy airbases. Such detection capabilities allow the defending side to better prepare its ground- and air-based defenses before the penetrators even reach the engagement zones. The factors that contribute to this determination include:[7]

- Range and effectiveness of defender's radar and other sensors.
- Number of penetrators taking off/marshalling.
- Signatures and cross-sections of the penetrator aircraft.
- Level of penetrator jamming activity (against radar and communications).
- Level of penetrator airborne radar and communications activity.

The second part determines the sequence of ground-to-air, air-to-air, and air-to-ground engagements that will be encountered by the penetrating aircraft on ingress and egress. Since the model knows the flight path (or assumed flight path in the low-resolution model), the possible sequence of engagements may be calculated. The actual engagement sequence will depend on whether or not the penetrators have been identified, and whether or not there are defending assets available and allocated to engage these penetrators. The model must know when to check for a *possible* engagement, even if the model determines that no engagement occurs in this situation.[8]

[7]A later version of the TLC/NLC model may include the ability to intercept penetrating aircraft as they are marshalling.

[8]The model user can have a significant input in the sequence of possible engagements. The user defines the engagement zones and the penetrator routes. Where the routes intersect the engagement zones determines the sequence of possible engagements. Whether or not missiles are actually launched depends on many factors, such as the detection probability, allocation decisions,

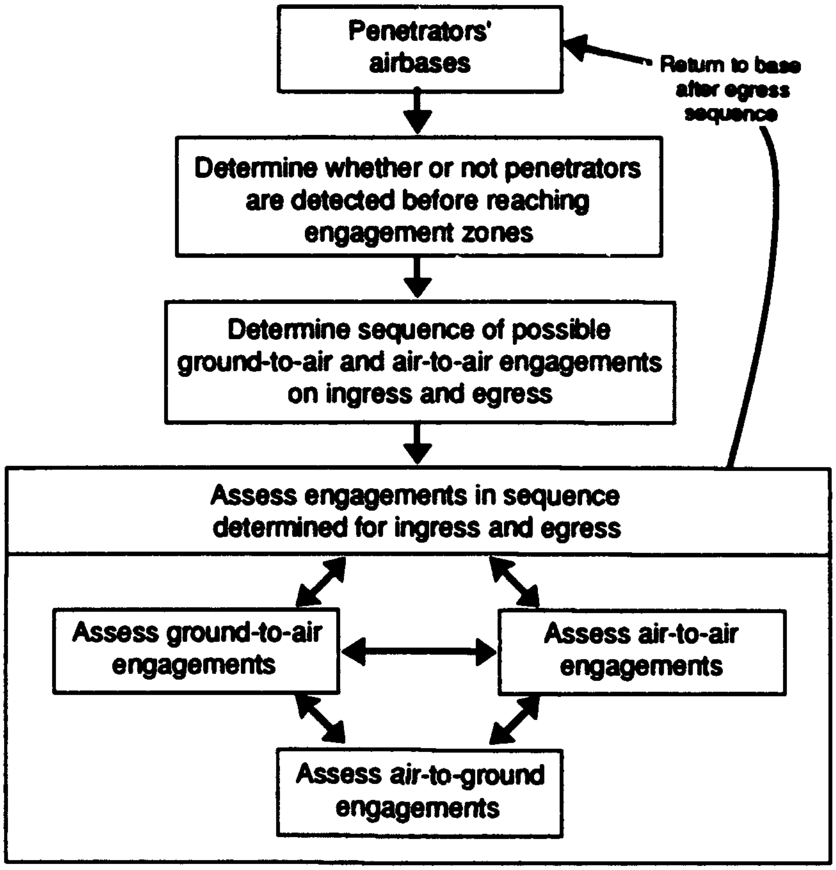


Figure 2.1—Overview of Air Combat Assessment Process

In TLC/NLC, a separate engagement is determined each time the flight or flight group enters a new section of the network, as defined by a SAM zone, an AAA zone, a CAP zone, or the target air defense zone. SAMs in a SAM zone are assumed to be uniformly distributed for each type of SAM, as are AAA assets in an AAA zone. The target may lie in any of these three types of zones (SAM, AAA, or CAP), and may also have terminal defenses associated specifically with the target.

The ground-to-air engagement zones may overlap each other and air-to-air engagement zones, thereby requiring multiple assessments for that segment of the network. (See Figure 2.2 for an example of sequencing engagements in overlapping networks and the appendix for a more detailed discussion of efficiently calculating the geometry associated with a sequence of engagements.)

---

and other factors that the user can also influence. The model does not allow for "chance" engagements not already included in the sequence of events.

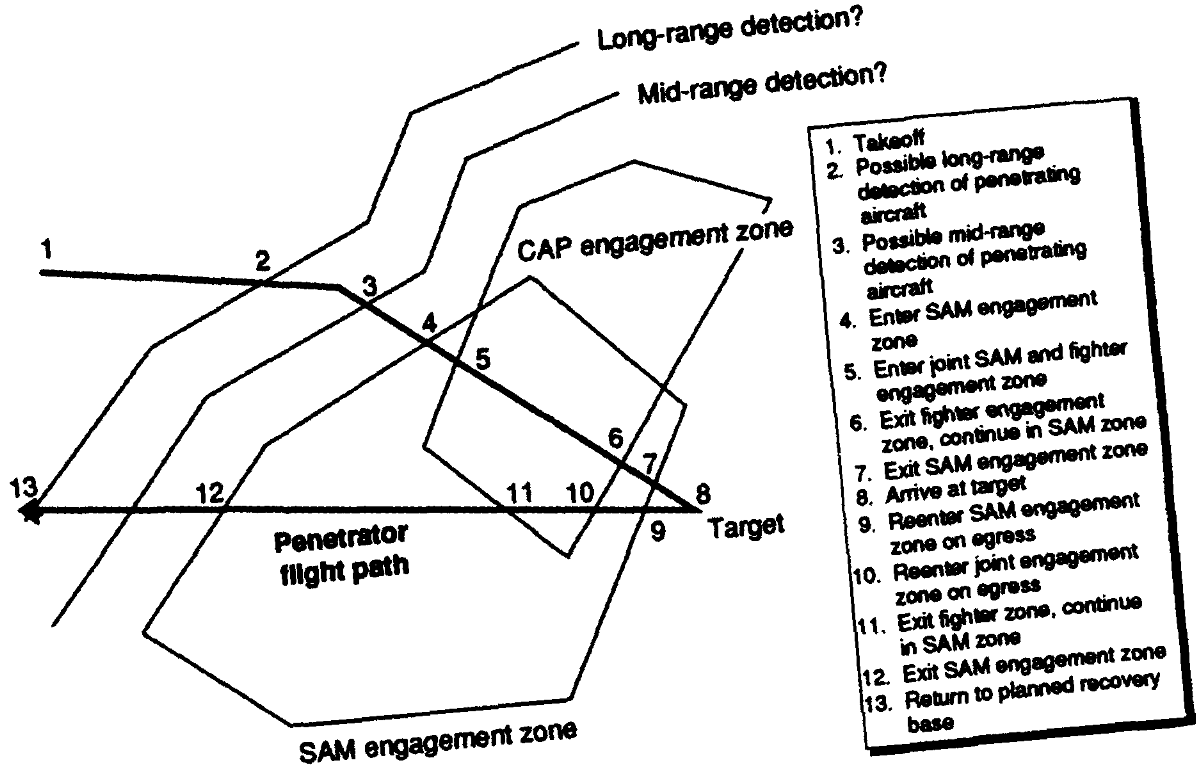


Figure 2.2—Example of Determining Sequence of Engagements

For a lower-resolution version, one could specify that the penetrators encounter a fixed sequence of defenses. For example, the model user may choose to enter a SAM belt first, followed by an interceptor or CAP zone, and then terminal defenses, and the reverse process on egress. One could also vary the sequence in the low-resolution model to represent different air defense strategies on the part of the defender. A sample sequence of events and engagements based on Figure 2.2 is given below:[9]

[9]Note that there is no adaptive mission rerouting explicitly represented in this model. Locating secondary targets and mission aborts are handled implicitly rather than explicitly. Mission aborts could occur at almost any time in the mission. There are usually two ways to resolve mission aborts: Return the aborting aircraft to their base immediately, or create a separate flight and explicitly return the new flight through the sequence of events en route to the airbase. The former method is probably the one that will be used most often in the model. Flight groups (or raids or packages) consist of more than one flight, while a flight usually consists of about four aircraft.

1. Takeoff.
2. Possible long-range detection of penetrating aircraft.
3. Possible midrange detection of penetrating aircraft.
4. Enter SAM engagement zone.
5. Enter joint SAM and fighter engagement zone.
6. Exit fighter engagement zone, continue in SAM zone.
7. Exit SAM engagement zone.
8. Arrive at target.
9. Reenter SAM engagement zone on egress.
10. Reenter joint engagement zone on egress.
11. Exit fighter zone, continue in SAM zone.
12. Exit SAM engagement zone.
13. Return to planned recovery base.

Of course, different sequences of events and engagements may occur, depending upon the flight path, the number of SAM zones, the number of AAA zones, and the number of CAP zones. For example, the target may lie in a SAM zone and an AAA zone, in addition to the terminal defenses specifically protecting that target. In that case, the SAM and AAA engagements will be assessed on ingress before the terminal defenses at the target engage, and then the SAM and AAA zones will also engage the penetrators on egress as well.

The third part actually assesses the ground-to-air, air-to-air, and air-to-ground engagements in the sequence defined in part two. The details of each of these three types of engagements will be addressed below. At the moment, it is assumed that a flight or flight group will continue on the flight path unless all of the aircraft have been destroyed or the group aborts its mission.[10]

After crossing the last engagement zone, the aircraft return to base. (This document will not address the issue of aircraft making unscheduled returns to other bases because their base was closed during their mission.) Note that the model's *process* to determine the sequence of assessment events is the same for each side (Blue and Red).

[10]However, the probability of reaching the primary or secondary target will be a function of the degree of evasive action required, and the penetrating flight group's decision rules. See the text associated with Figures 5.1 and 5.2.

3. AIR-TO-AIR ENGAGEMENTS

Air-to-air engagements may be divided into a series of "rounds." In a lower-resolution version of the model, there could be simply one round of air-to-air engagements. In a more detailed version of the model, there may be more than one round of air-to-air engagements. In this example for TLC/NLC, we assume that a first round pits interceptors against escorts and against some bombers, while the second round allows surviving engaged interceptors to further engage remaining escorts and bombers. There may be many combinations of defined "rounds" in different versions of the model (see Figure 3.1). TLC/NLC has also been designed to allow for a single-round BVR (beyond visual range) engagement.

There are three basic steps to each round. The first step is to determine the number of interceptors that can intercept the penetrators. The second step is to determine the number of escorts, sweep aircraft, or bombers that engage these interceptors.

The second round is very similar to the first round, thereby allowing the use of the same code with a different set of starting numbers. In the first step of the second round, the interceptors that survived the first round of engagements are allowed to try again to reach the bombers. If escorts remain that were not engaged in the first round, some may attempt to intercept the interceptors, just as in the first round. The unengaged interceptors may engage the bombers (and vice versa) during the second round, subject to the detectability of the bombers. These engagements are then assessed in the same manner as before.

Note that when defining the number of rounds and who can engage whom, one must keep in mind that a number of assumptions are being made in each case. For example, allowing surviving interceptors to engage for a second round assumes that the interceptors are not at the limit of their operating range (fuel status), and did not consume all of their ordnance in the first round. Alternatively, one may assume that escorts that did engage in the first round may have to return to base due to lack of remaining fuel and ordnance. One may either explicitly track the ordnance and fuel state of each aircraft, or of each flight, or make some assumptions about the fuel and ordnance state as a function of the preceding engagement. The details of each of the three steps are given below.

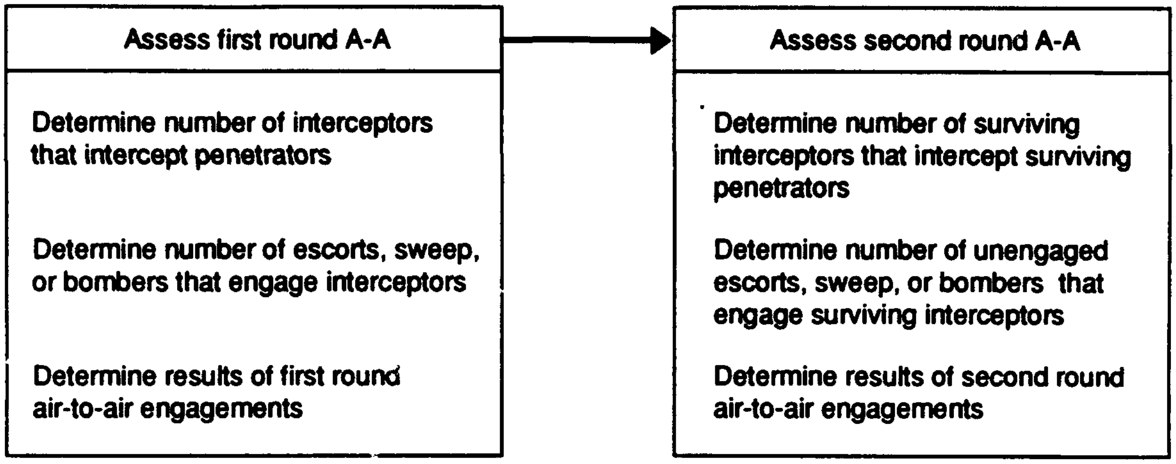


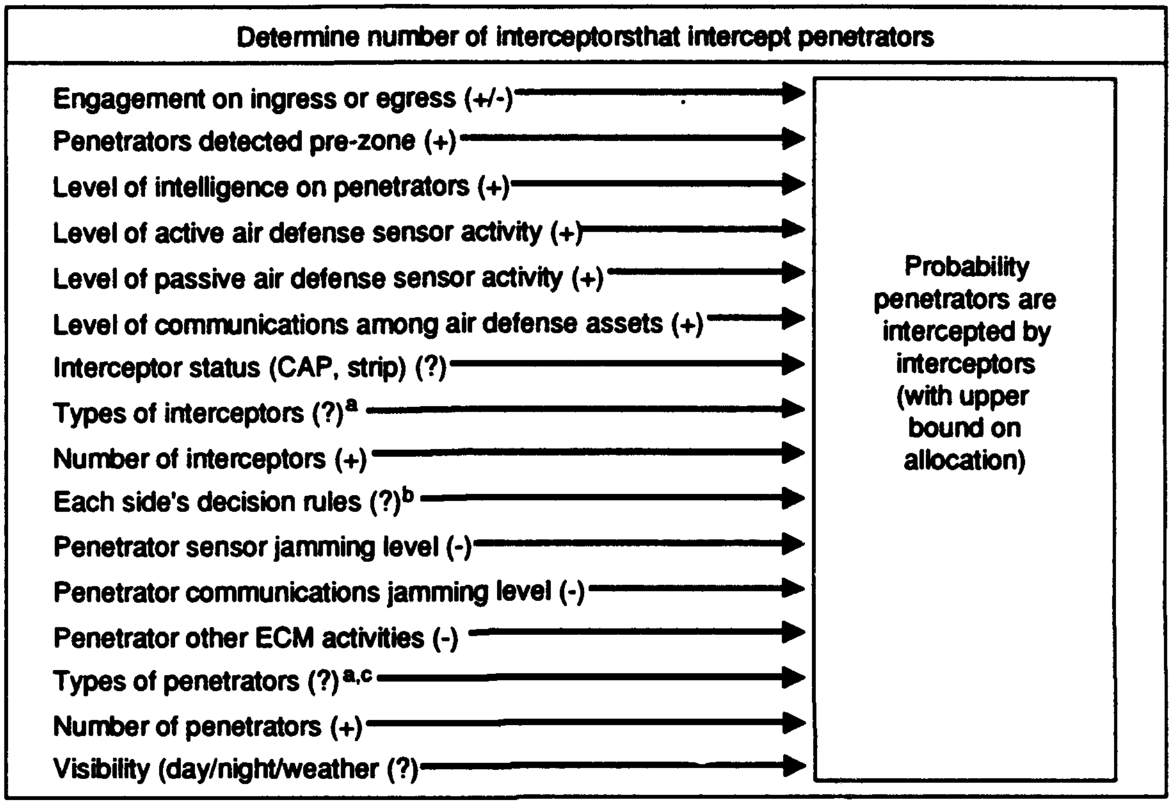
Figure 3.1—Air-to-Air Engagement Assessment Process

DETERMINE NUMBER OF INTERCEPTORS THAT INTERCEPT PENETRATORS

The key parameter in this step is "the probability that the penetrators are intercepted by interceptors." This parameter definition is applicable to the stochastic and deterministic versions, as well as to the high- and low-resolution versions. For example, in a low-resolution version, this probability can be defined by fiat, while in a higher-resolution version, this probability may depend on a number of parameters, as shown in Figure 3.2. (The plus symbols mean that as the value of this factor increases, the resulting probability also increases. A negative symbol means the opposite. A question mark means that it can go either way, depending upon the values. In the detailed design, the magnitude and form of the effect will be discussed, as well as the degree of model user control over these parameters.)

Similarly, in the deterministic version, given the number of interceptors available, that number times this probability determines the number of interceptors that can engage the penetrators in this cycle. In the stochastic version, a random number is generated to determine whether or not a given CAP flight or flight on strip alert will be able to engage given that same probability.

Due to the wide range of possible number of engagements and sizes of engagements over time, it is recommended that in any version of the model, an upper bound be applied to the number of interceptors that can be *allocated* against the penetrators. For example, in the TLC/NLC model, another flight group may be following close behind this first group of penetrators. Rather than allocate all 100



[a] Includes different aircraft types, nationality, training, air-to-air munitions types, on-board sensors, and associated reliability factors for each type aircraft.

[b] Includes prioritization, allocation, and decisions given the perception on each side.

[c] Includes decoy penetrators as well as actual penetrators.

Figure 3.2—Probability That Penetrators Are Intercepted

interceptors against the first flight group, the air defender will probably choose to allocate some ratio of interceptors to penetrators. This ratio might be close to a 1:1 ratio subject to the known quality of the aircraft. For example, a threat air defender may prefer a 1.5:1 upper bound, while a U.S. air defender may opt for a 0.9:1 upper bound. Other more sophisticated allocation approaches could also be employed, such as allocating the number of air defense aircraft as a function of the value of the target being defended. In TLC/NLC, the plan is to base the allocation on weighted interceptor and attacker values. The values will be defined for combinations of the type aircraft and weapon load based on Tac Brawler outputs.

This upper bound can help preclude unusual situations where all of the interceptors are "expended" against a small group of penetrators, while a larger and more important group of penetrators flies through undefended areas. One may also

wish to make this upper bound a function of the information available to the air defender as well as his ability to communicate with his airborne interceptors. All of the decision rules will be based on the perceived situation as viewed from each side and not on perfect information (although one should be able to assume perfect information for purposes of analysis).

In either the deterministic or stochastic version of the model, one will probably wish to vary the "probability that interceptors engage the penetrators" based upon a number of factors. These factors are discussed below.

The main factors in Figure 3.2 that affect the value of this probability are listed below:

Engagement on ingress or egress. The probability of interceptors intercepting penetrators is generally higher on penetrator ingress and lower on penetrator egress, subject to the location of the interceptor bases relative to the penetrator flight path.[11] In TLC/NLC, air-to-air and ground-to-air engagement zones are given an orientation to better handle nonlinear geometries while determining engagement factors.

Penetrators detected pre-zone. If the penetrators are detected before they reach the first air-to-air engagement zone with sufficient warning time, then the air defenders may be able to be better prepared to engage the penetrators. Note in the overview section that the determination was made whether or not the penetrators were detected before reaching the first engagement zone. For air-to-air engagements, an adjudication point is determined in the air-to-air region as a function of the probability of detection. One important factor to consider is that the escorts and the bombers of the penetrators may not have equivalent signatures. Therefore, the model should allow for different detection rates for interceptors against escorts and bombers as a function of detectability.

Level of intelligence on penetrators. If the defender has sufficient intelligence on the components of the raid, he may be better able to allocate his air defense assets against the high-value penetrators and avoid high-threat penetrators, or to ignore decoy platforms.

Level of active air defense sensor activity. Active air defense sensor activity includes radars and other sensors that transmit a signal of some sort. The

[11]The probability of intercept is also a function of the air defender's perception of the situation, priorities, and allocation decision rules. See "each side's decision rules" later in this section.

more an air defense radar is active, the more likely that the penetrators will be tracked and the interceptors vectored to the appropriate intercept point. However, this factor will also work to the advantage of the enemy SEAD aircraft attempting to destroy or suppress the air defense radars. (See the section on ground-to-air engagements for more details.) One may wish to set the air defense radar activity at predefined levels, such as emissions control levels (EMCON) used by the U.S. Navy and some NATO nations.

Level of passive air defense sensor activity. Passive air defense sensor activity includes optical sensors and other sensors that do not transmit a signal. The more air defense radar is active, the more likely that the penetrators will be tracked and the interceptors vectored to the appropriate intercept point. Although many countermeasures can be used against passive air defense sensors, it is more difficult to detect the location or activation of passive detection devices.

Level of communications among air defense assets. Even though the radars may detect the penetrators, this information is useless unless the information can be passed to the intercepting aircraft, whether they are airborne or on strip alert. If the communication between airborne interceptors and their control center (AWACS or GCI) is suppressed, the ability to intercept will be significantly reduced. If there are future types of aircraft that have as good or better on-board sensors as AWACS or GCI, then these interceptors will be less affected by a lack of communications.

Interceptor status. This factor is designed to implicitly account for the geometry and timing of intercept between interceptors and penetrators. For example, interceptors on CAP can more easily engage penetrators crossing their engagement zone than can aircraft on strip alert. The ability to engage within the zone may be specified by fiat, or made a function of the range from the bases to the engagement zone and the warning time available to reach the zone from the interceptor base. There is no explicit representation of the geometry of intercept at this level of aggregation, but the effects of geometry and timing are included in the selection of the intercept point in the CAP engagement zone.

Number of interceptors. The higher the number of interceptors within the same operating area, the easier it will be for the interceptors to engage the penetrators. One may wish to replace this variable with the density of interceptors per given area.

Types of interceptors. Different types of interceptors will have different types of capabilities against various types of penetrators. The factors considered

within the type of interceptor include the type of aircraft, its nationality, level of pilot training, the types of air-to-air munitions, any on-board sensors, and the reliability associated with these factors. Note that a combination of the above factors will help determine the aircraft's speed, detectability, lethality, and vulnerability.

Each side's decision rules. Each side uses three primary types of rules: the prioritization and allocation of assets against the opposing side's assets, the rules of engagement, and the rules of disengagement. The allocation rules include which types and how many assets will be allocated against which enemy assets.

For example, a flight group may allocate a four-ship group of escorts to engage a four-ship group of interceptors, while retaining a second four-ship group of escorts to handle the next threat. The first four-ship group of escorts may or may not expend all of its munitions and fuel to defeat the interceptor. If too many munitions or too much fuel has been expended, the aircraft return to base, otherwise, they attempt to rejoin the penetrating flight group. Allocation rules could also be defined for a desired level of damage or destruction against enemy aircraft, as opposed to a ratio of number of assets.

The rules of engagement include decisions such as allowing for BVR engagements. Rules of disengagement include rules such as the fuel and missile status thresholds before deciding to disengage. The reason that both sides' decision rules are considered together is that the resulting assessment process is a function of the combination of each side's decision rules (based on each side's perceptions), rather than each side's decisions considered separately.

One important issue raised is that in a more complex shooter-rich target-rich environment, there is likely to be more cases of double allocation, or missed allocation, or even fratricide. The allocation rules used by each side should not be based on perfect information but on hedging under uncertainty. How this factor will be included in the model is not currently known.

Penetrator active sensor (radar) jamming level. The more the penetrators jam the defender's radars, the more difficult it will be for the defender to precisely vector interceptors to a favorable engagement point. Jamming for the penetrators may be provided by aircraft in the same flight group, or may be provided by separate standoff aircraft. Note that airborne jamming in support of penetrators also can work against the penetrators, resulting in detection before the first engagement zone. The enemy's radar screen might not reveal exactly where aircraft are or how many there are, but it will reveal that somebody is coming. (Not

representing this effect has been a problem in most air combat models.) That is one of the advantages of stealth technology--the ability to slip in undetected (depending upon the type of radar or other sensors being employed). At the same time, the penetrators can use jamming as part of a deception operation, or to "desensitize" the defender against sudden changes in penetrator activity.

Penetrator communications jamming level. This factor is similar to jamming radars, except that the focus is on jamming the air defender's ability to guide his interceptors from a central control. The greater the degree of communications jamming, the lower the probability of intercept by the interceptors. Since communications jamming for the penetrators is not usually provided by aircraft in the the same flight group, it is usually provided by separate standoff aircraft.

Penetrator other ECM activities. If any other forms of counter C3 support are being applied, they should be included here. For example, special forces operations against C3 sites should be included here.

Types of penetrators. Just as the types of interceptors matter, so do the types of penetrator aircraft. The type of penetrator varies due to type of aircraft, its nationality, level of pilot training, type of air-to-air munitions, on-board sensors, and associated reliabilities. For example, self-escorting bombers will act differently than escorts or unprotected bombers. Also, different types of aircraft will have different cross-sections as a function of the types of sensors. For example, a low-observable penetrator will be harder to detect than will a more traditional penetrator aircraft. Decoy platforms should be included as distinct types of penetrator platforms.

The number of penetrators. The larger the number of penetrators in an engagement area, the larger the probability of engagement. Large raids are easier to detect through local search techniques even in the absence of a central control. In the days when aircraft might have been flying in waves of 100 aircraft each wave, flying in three waves and stretched for kilometers, the probability of intercept was significantly higher.

Although the number of engagements tends to increase with the number of targets, at some point the shooters become saturated with possible targets. Therefore, the number of engagements is also limited by the number of shooters. When the shooters are saturated by too many targets, there is an upper bound on the number of ground-to-air engagements.

Visibility (day/night/weather). Greater visibility allows interceptors a better chance to detect and engage penetrators. Simple visual cues, such as glint off

of a cockpit canopy or metal, can attract a pilot's attention to a penetrating aircraft. In TLC/NLC, weather regions are defined by visibility, ceiling, temperature, and other factors.

The preceding factors may be defined by the analyst, or may in turn be a function of other parameters. For example, one could determine a probability of interception from a higher-resolution model and use these factors as a way to increase or decrease the given probability. However, it is recommended that one not have too many layers of dependence so that the model remains understandable and the effects of the same input parameters are not double counted.

In TLC/NLC, many of the preceding factors such as AWACS, GCI, and jamming are currently represented as "yes or no" variables. These variables can be expanded to account for a wider space of option and values as the need arises. The reason for not explicitly modeling the operation of AWACS or GCI is that they have such far-reaching effects. For purposes of analysis, one would want to run cases where AWACS or GCI were operational, and other cases where they were suppressed or destroyed. The model is designed to account for their effects on combat operations, but not to explicitly represent the orbits, flight plans, and evasion criteria and techniques of these assets.

DETERMINE NUMBER OF PENETRATORS THAT ENGAGE INTERCEPTORS

The key parameter in this step is "the probability the interceptors are intercepted by escorts, sweep aircraft, or bombers." This parameter definition is applicable to the stochastic and deterministic versions, as well as the high- and low-resolution versions, in a similar manner as described above.

This probability should also have with it a factor that limits the *allocation* of escorts against interceptors. For example, the penetrating flight group will not wish to allocate all of its escorts against a single flight of interceptors. Therefore, an upper bound needs to be applied to the number of escorts allocated to each group of interceptors. This ratio may be close to a 1:1 ratio subject to the *known* quality of the aircraft, as described above. This ratio should be a function of the *perceived* interceptor threat so that deception operations to distract escorts away from real targets could be played. Two effects of uncertainty might be represented in the model: cases where the number of escorts allocated against an interceptor threat

may be larger than necessary due to uncertainty, and cases where the opposing side attempts to exploit that level of uncertainty by using deception operations.[12]

The following list of factors (see Figure 3.3) is similar to that above, and therefore will not require as detailed a description. However, where differences occur, they will be highlighted.

Engagement on ingress or egress. The ability of escorts, sweep aircraft, or bombers to intercept interceptors is higher on ingress than on egress, subject to the same geometry as described above. Orientation is a more general terms for this.

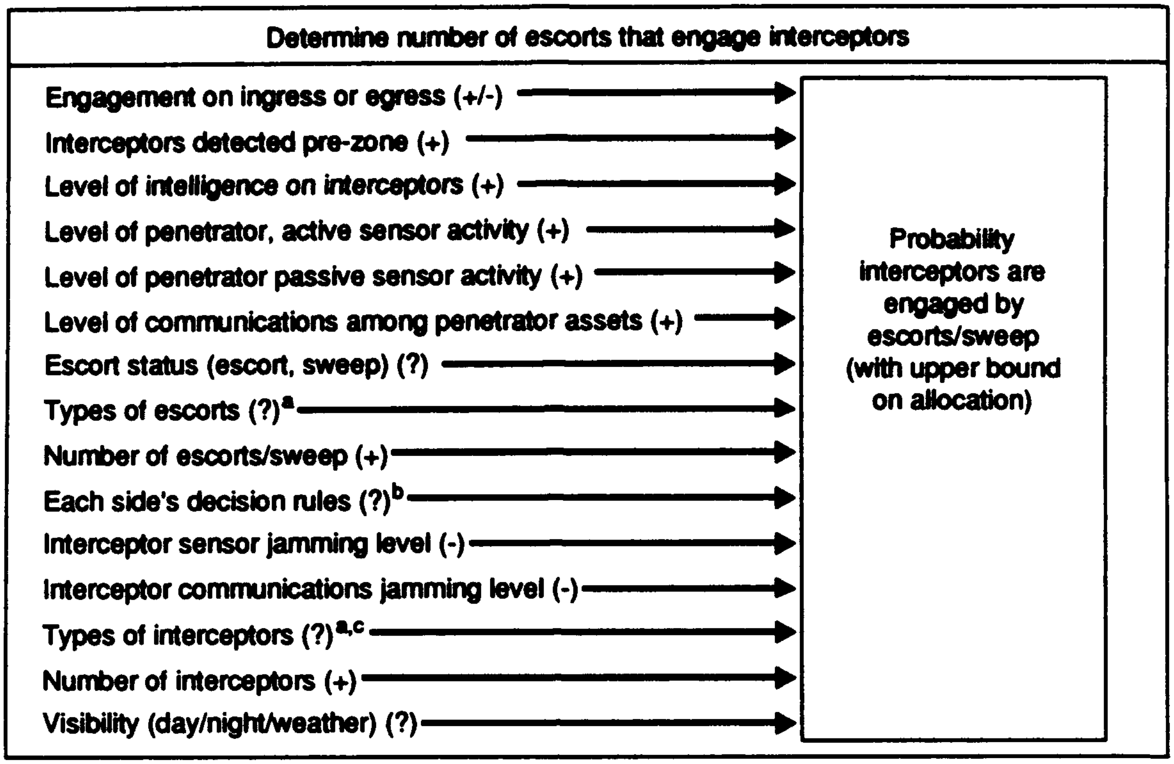
Interceptors detected pre-zone. With modern airborne radar, it is often possible to detect enemy interceptors on CAP or rising from strip alert. As a result, the penetrators can be better prepared to meet these threats before entering the engagement zone. (The detailed design plan is to define decision rules so that if one side knows it is outclassed, it will attempt to avoid the engagement unless explicitly ordered to engage. Similarly, if the penetrators have not detected the interceptors before they fire, the interceptors will have a significant advantage during the first round of the engagement. The converse is also true.)

Level of intelligence on interceptors. If the attacker has sufficient intelligence on the components of the air defenders, he may be better able to allocate his escorts against the most lethal interceptors.

Level of penetrator active sensor activity. The ability of the penetrators to detect enemy interceptors will increase as a function of their active sensor activity, such as radar. However, there are tradeoffs to this capability. Due to range limitations, this capability must often be carried aboard the penetrators rather than as a standoff capability. However, the effects of any standoff aircraft supporting this mission must still be considered. (In either case, the ability to communicate between aircraft will still be essential to using this capability. See "level of communications" below.)

Level of penetrator passive sensor activity. The ability of the penetrators to detect enemy interceptors will increase as a function of their passive sensor activity, such as enhanced optics. Passive sensor activity is subject to

[12]Note that self-escorting air-to-ground aircraft may be allocated as escorts in the model. Given appropriate higher-resolution Tac Brawler runs, the results of engagements where aircraft jettison their air-to-ground munitions for better survivability and lethality should be represented in the model. That would also mean that aircraft that jettison their air-to-ground munitions instantly abort their air-to-ground mission.



[a] Includes different aircraft types, nationality, training, air-to-air munitions types, on-board sensors, and associated reliability factors for each type aircraft.

[b] Includes prioritization, allocation, and decisions given the perception on each side.

[c] Includes decoy interceptors, if any.

Figure 3.3—Probability That Interceptors Are Intercepted

countermeasures, but not to the countermeasures that are used to disrupt active sensors.

Level of communications among penetrators. If the penetrators can communicate well among themselves and a central control, the ability to intercept the interceptors will be greater. This separate control may be provided by a standoff aircraft supporting the mission.

Escort status. Aircraft on sweep missions have more freedom in engaging potential enemy interceptors and prosecuting those engagements. However, they are less likely to be closely attached to penetrator flight groups for close escort purposes, especially on egress. Escorts are more closely tied to the flight group they are escorting, but also less able to intercept the interceptors before they engage the bombers.

Types of escorts. Same as types of penetrators, above.

Number of escorts or sweep aircraft. The larger the number of escorts or sweep aircraft, the more likely they will be able to force an engagement with enemy interceptors. As in the previous section, this factor may be replaced by the density of escort or sweep aircraft.

Each side's decision rules. Same as above.

Interceptor sensor jamming level. If the air defender uses radar jamming (unlikely but possible), then the ability of the escorts to intercept the penetrators will decrease. Note that even if the penetrator level of radar jamming activity is high, the ability of the escorts to intercept the interceptors may still be reduced.

Interceptor communications jamming level. As above, the air defender is less likely to jam communications so as to enhance the ability of his interceptors to intercept the penetrators. However, even if the penetrator jamming level is high, the penetrating escorts will find it more difficult to communicate and thereby lower the probability of intercepting the interceptors before they reach the bombers (subject to communications susceptibility to such jamming techniques). Standoff or ground-based assets may support this mission.

Types of interceptors. Same as above.

Number of interceptors. Just as it is easier to intercept a large group of penetrators, it is also easier to intercept a large group of interceptors. The more interceptors that approach the penetrating flight, the more escorts can be allocated to intercept them. At the same time, there may be more interceptors than escorts can handle, thereby saturating the escort defenses.

Visibility (day/night/weather). Just as good visibility makes it easier to detect penetrators, good visibility makes it easier to detect interceptors.

DETERMINE RESULTS OF AIR-TO-AIR ENGAGEMENTS

One main purpose of this air combat model design is to allow this model to be calibrated to higher-resolution air combat models, such as Tac Brawler. One limitation of the TAC Thunder model has been the difficulty in calibrating the inputs of TAC Thunder to the outputs of models such as Tac Brawler. This design should allow for such calibration and also for assessment in the absence of a sufficient number of high-resolution model runs to cover all of the possible cases.

For example, penetrating aircraft may choose to jettison their air-to-ground munitions to have a better chance of survival or escape in an air-to-air engagement. Different Tac Brawler runs should be made for engaged air-to-ground aircraft with

and without air-to-ground munitions still on board. The results of the Tac Brawler runs will be used to calibrate cases with and without air-to-ground munitions on board in TLC/NLC runs. Note that if the penetrators choose to jettison their air-to-ground munitions, their air-to-ground mission is aborted whether or not they survive the air-to-air engagement.[13]

The outputs of this section will include the number of penetrators destroyed (by type), the number of interceptors destroyed (by type), the number of interceptors and penetrators that can continue their mission, and the expenditures of consumables by each side. (Munitions remaining on destroyed aircraft are considered destroyed as well.) The design assumes that at the end of a given engagement, some aircraft will have a fuel or munitions state requiring them to return to base. We hope to be able to track a general fuel and munitions state for the flight, decremented as the result of the outputs of detailed models, so that we do not need to track the fuel supply and weapons of each aircraft.[14] The aircraft available to continue combat may be allowed to enter another engagement, depending on the outcome of this engagement and each side's rules of disengagement.

Regarding the distribution of losses of aircraft by type, there are many alternative extrapolation schemes. One proposed method is to determine the number of losses first, and then to distribute those losses among types of aircraft. For example, in the first round, three types of interceptors may be engaged against two types of escorts, and three types of interceptors may be engaged against four types of bombers and mission support aircraft. Once the total number of interceptors is determined in each case, the distribution of the number of interceptors for each aircraft is then determined. We are examining alternative loss distribution formats similar to some already successfully applied to ground combat assessment models. One possible factor in the distribution of penetrator losses could be the intelligence available on the component types of aircraft in a raid.

Once again, one may define the number of losses by fiat (such as a percentage of aircraft lost per sortie), or one may wish to represent these losses as a function of the following factors (see Figure 3.4).

---

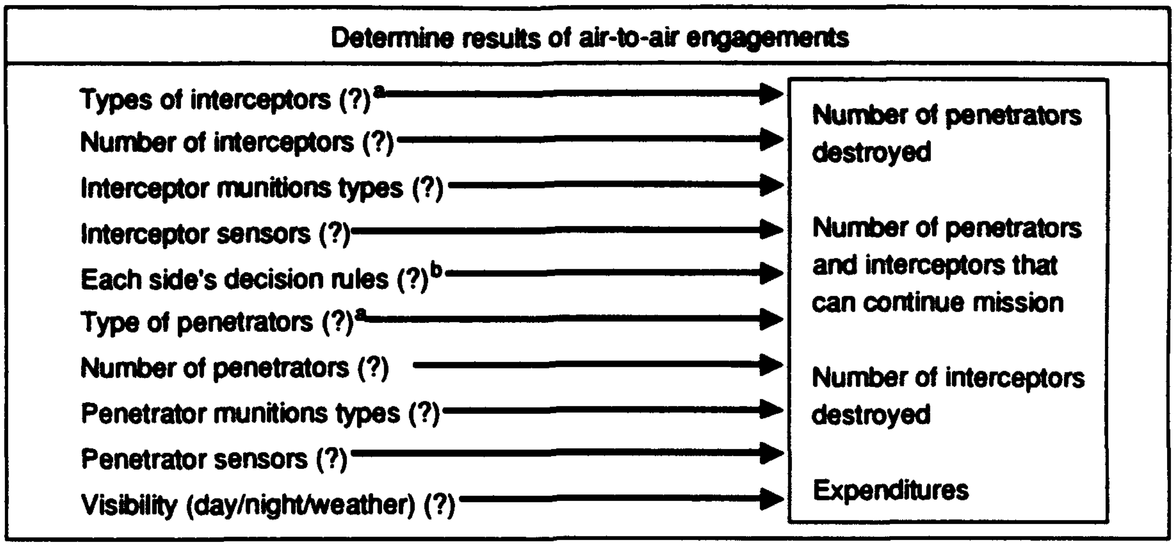
[13]As long as the aircraft tactic or feature can be represented in Tac Brawler, we should be able to use the data to calibrate to TLC/NLC. If, however, the tactic or feature of a specific type of aircraft cannot be represented in Tac Brawler (such as interceptors attempting to ram penetrating aircraft), then we will probably not be able to include it in the TLC/NLC model.

[14]At the moment, we do not plan to keep track of survival expendables, such as flares, chaff, and other single-use assets, in a given flight.

The loss rates for each side tend to be independent of whether the engagement occurs on ingress or egress. The only other preceding input factors that may require explanation include the types of munitions and the types of sensors. The type of munition will tend to give certain types of aircraft more of an advantage. For example, BVR munitions allow engagement of enemy aircraft before they get into range with their weapons. However, unless the side with those munitions has a rule of engagement procedure allowing for the use of BVR munitions, these weapons cannot be used to their full advantage. Similarly, if BVR weapons are employed, the model must also account for air-to-air fratricide.

The types of on-board sensors may also play a crucial part in the engagement outcomes. For example, certain types of radars are very susceptible to certain air-to-air maneuvers, while others are not. Similarly, advanced optical sensors are likely to reemerge as a vital on-board sensor, especially because of the availability of stealth technology. In addition, visibility conditions may affect the loss rates on each side.

As a final point in this subsection, the air-to-air assessment results should be a function of the overall size of the engagement. If few aircraft are engaged overall, the loss of one or two aircraft may cause the remainder to abort their mission. If many aircraft are engaged, the breakoff threshold may be more a matter of the perceived fraction of losses. At this time, it is uncertain what these thresholds should be, or even if they should be used at all.



[a] Includes different aircraft types, nationality, training, air-to-air munitions types, on-board sensors, and associated reliability factors for each type aircraft.

[b] Includes prioritization, allocation, and decisions given the perception on each side.

Figure 3.4—Air-to-Air Engagement Results

4. GROUND-TO-AIR ENGAGEMENTS

The ground-to-air engagement assessment process is somewhat similar to the air-to-air process, but with the following differences. First, there are no "rounds" as in air-to-air engagements, although one could define such rounds if the continuous exposure time of the penetrators were sufficiently long. For example, long-range ground-to-air assets may be able to perform shoot-look-shoot engagements during a single ground-to-air engagement round. One way to represent this capability is to allow long-range SAMs to include multiple engagement points within the SAM engagement zone.

While the air-to-air assessment process will tend to assess the results of many-on-many engagements as the results of several few-on-few engagements, the ground-to-air assessment process will probably be assessed simultaneously against the whole package or flight group. The second difference is that there are four steps to the ground-to-air process (see Figure 4.1).

DETERMINE NUMBER OF SAM AND AAA ENGAGEMENTS AGAINST PENETRATORS

The key parameter in this step is "the probability the penetrators could be engaged by SAMs or AAA."[15] This parameter definition is applicable to the stochastic and deterministic versions, as well as the high- and low-resolution versions, in a similar manner as described above.

This probability should also include firing doctrine that limits the allocation of SAMs firing against penetrators. For example, the SAMs will probably not wish to expend all of their munitions against a single flight of penetrators. Therefore, an upper bound needs to be applied to the number of SAM engagements allocated to each penetrator. This ratio will probably be close to 1:1 subject to the known or perceived quality of the SAMs, as described above. Just as different types of intercepting aircraft may employ different allocation schemes, so may different types of SAMs.

[15]It is assumed that anti-aircraft artillery (AAA) and surface-to-air missiles (SAMs) will be included in separate ground-to-air engagement zones for ease of assessment processing. Although AAA tends to be less accurate than a SAM, it is harder to suppress AAA. AAA and SAM zones may overlap in TLC/NLC. As a reminder, SAM assets by type are uniformly distributed across the SAM zone, while AAA assets by type are uniformly distributed across AAA zones.

Determine number of SAM and AAA engagements against penetrators

Determine number of SEAD engagements against engaging SAMs and AAA

Determine results of SEAD engagements against SAMs and AAA

Determine results of SAM and AAA engagements against penetrators

Figure 4.1—Assessing Ground-to-Air Engagements

The following list of factors (see Figure 4.2) is similar to those listed above, and therefore will not require as detailed a description. However, where differences occur, they will be highlighted.

Engagement on ingress or egress. Same as defined for air-to-air engagements, including the need to account for the orientation of the engagement.

Penetrators detected pre-zone. Same as above.

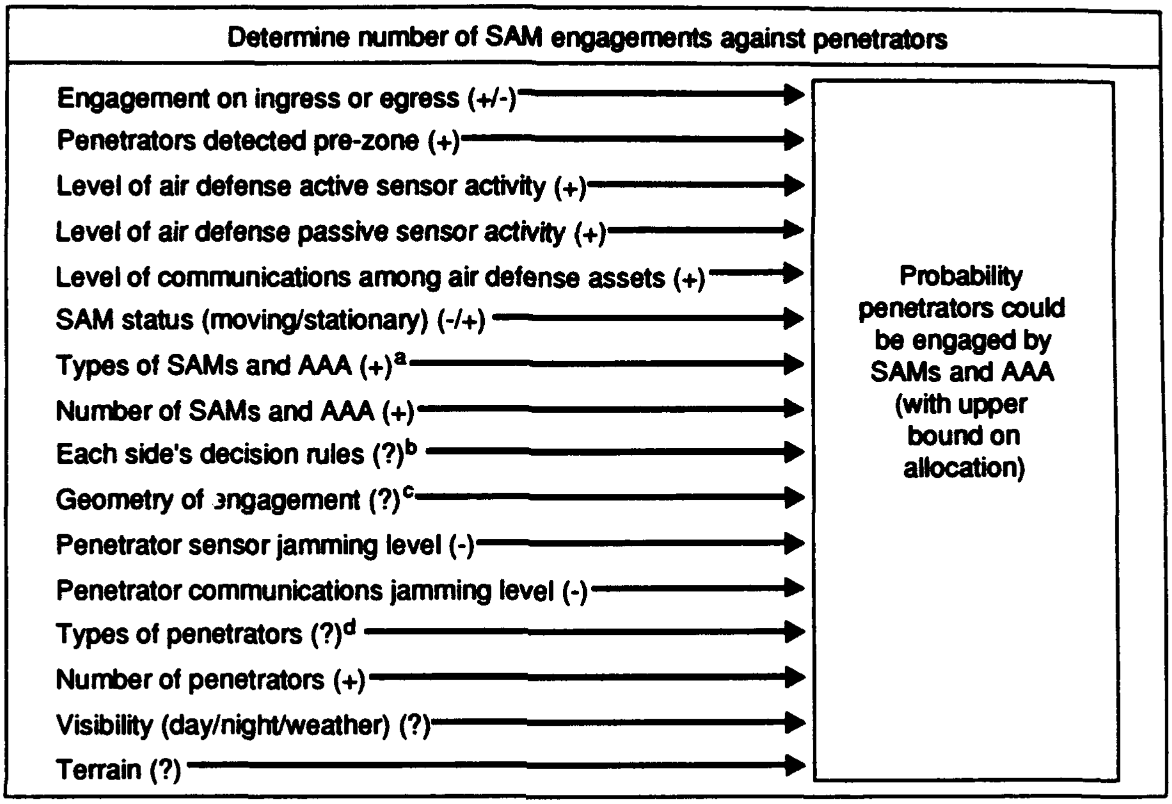
Level of active air defense sensor activity. Same as above.

Level of passive air defense sensor activity. Same as above.

Level of communications among SAMs. One distinction about jammed SAM sites is that the engagement rate may actually increase as a result of communications jamming. For example, former Soviet doctrine specified that if SAM sites lose communications with their control while under jamming, they are to go autonomous and launch at will. The model will need to be able to represent such doctrinal differences, as well as the vulnerability of such tactics to deception as during the Bekaa Valley campaign.[16]

SAM status. For a number of reasons, a SAM site may not be prepared to engage penetrating aircraft. For example, the SAM site may be reloading missiles, may be down for maintenance, may have few missiles remaining, may be inactive for self-protection, or may be moving. The SAM status will vary by type of SAM and the current situation. For example, a mobile SAM may be moving to better prepare for a

[16]There are tradeoffs with autonomous launches, such as multiple shots at a single target, no launch at other targets, limited coordination, and little warning time for each engagement. Note that if air space management rules are violated, fratricide will probably increase as well.



[a] Includes different SAM or AAA types, nationality, crew training, type munitions, sensors, and associated reliability factors for each type SAM or AAA.

[b] Includes prioritization, allocation, and decisions given the perception on each side.

[c] Includes aircraft altitude.

[d] Includes different aircraft types, nationality, training, air-to-air munitions types, on-board sensors, and associated reliability factors for each type aircraft.

Figure 4.2—Potential SAM Engagements

future engagement and is not currently available for this engagement. Fixed SAM sites are better prepared regarding their coverage and familiarity with an area of operations. However, they tend to be much more vulnerable to SEAD operations, as described in the next section. Conversely, mobile SAMs are less vulnerable to SEAD operations, but also less familiar with the area of operations. In addition, some fraction of the mobile sites will tend to be in motion during any given operation. These will tend to be less effective but more survivable.

Types of SAMs and AAA. Same as interceptors above.

Number of SAMs or AAA. Same as above.

Each side's decision rules. Same as above.

Geometry of engagement. This factor attempts to account for the amount of time each flight will be exposed to defending SAMs. This factor will be a function of the altitude and speed of the penetrating flight or flight group, the radar cross section of the flight or other detection cross sections, and the effective range of the SAMs and their radars in the SAM engagement zone. Note that if the aircraft are at very high altitude, most SAMs and existing AAA will not be able to reach them, while if the penetrators are low, the continuous exposure time will be reduced, especially in rough or mountainous terrain. However, low-altitude penetration increases the number of AAA sites that can engage the penetrators. In TLC/NLC, it is assumed that the resulting effective engagement range will define a "width" to the flight path that can then be used to assist in the calculation of the number of engagements (see the appendix). Within that potential engagement zone, the other factors listed will tend to increase or reduce the number of potential engagements. Note that this calculation is the most elaborate of these factors, and probably will require an additional level of input parameters to fully define.

Penetrator sensor jamming level. Same as above.

Penetrator communication jamming level. Same as above.

Type of penetrators. Same as above.

Number of penetrators. As with air-to-air engagements, the greater the number of penetrators, the higher the probability of engagement, but for different reasons. In the case of ground-to-air engagements, for example, a large number (e.g., hundreds) of penetrators may fly in column. As a result, air defenders have a better chance of engagement because they have already seen the first penetrators in the column go by, and have had a chance to identify the penetrator turn points (if any). However, low observable aircraft may fly alone or in small groups, and therefore would be more difficult to detect. Conversely, the number of detected penetrating aircraft may be so high as to saturate the defenses, thereby bounding the number of ground-to-air engagements.

Visibility (day/night/weather). The visibility will help determine the number of possible engagements, especially for AAA assets.

Terrain. The terrain may have an effect on the ability of SAMs or AAA to engage penetrating aircraft. If the terrain is very rough and the aircraft can perform terrain masking, then engagements of penetrating aircraft will be reduced. If, however, the SAM or AAA sites are on the mountains, the penetrating aircraft will

tend to remain in their field of fire longer, and therefore the engagement rate will increase.

DETERMINE NUMBER OF SEAD ENGAGEMENTS AGAINST ENGAGING SAMS

The key parameter in this step is "the probability the penetrator SEAD aircraft could engage SAMs that could engage the penetrators." This parameter definition is applicable to the stochastic and deterministic versions, as well as the high- and low-resolution versions, in a similar manner as described above.

This probability should also have with it a factor that limits the *allocation* of SEAD aircraft firing against detected SAM sites. For example, the SEAD aircraft will not wish to expend all of their munitions against a single SAM site. (Note that jamming by SEAD aircraft was already included in Figure 4.2. Figure 4.3 addresses only the issue of lethal suppression against air defense sites.) Therefore, an upper bound needs to be applied to the number of SEAD engagements allocated to each SAM site. This ratio of munitions expended per SAM site may be close to 1:1 subject to the known quality of the SEAD aircraft and the quality of the SAMs, as described above.

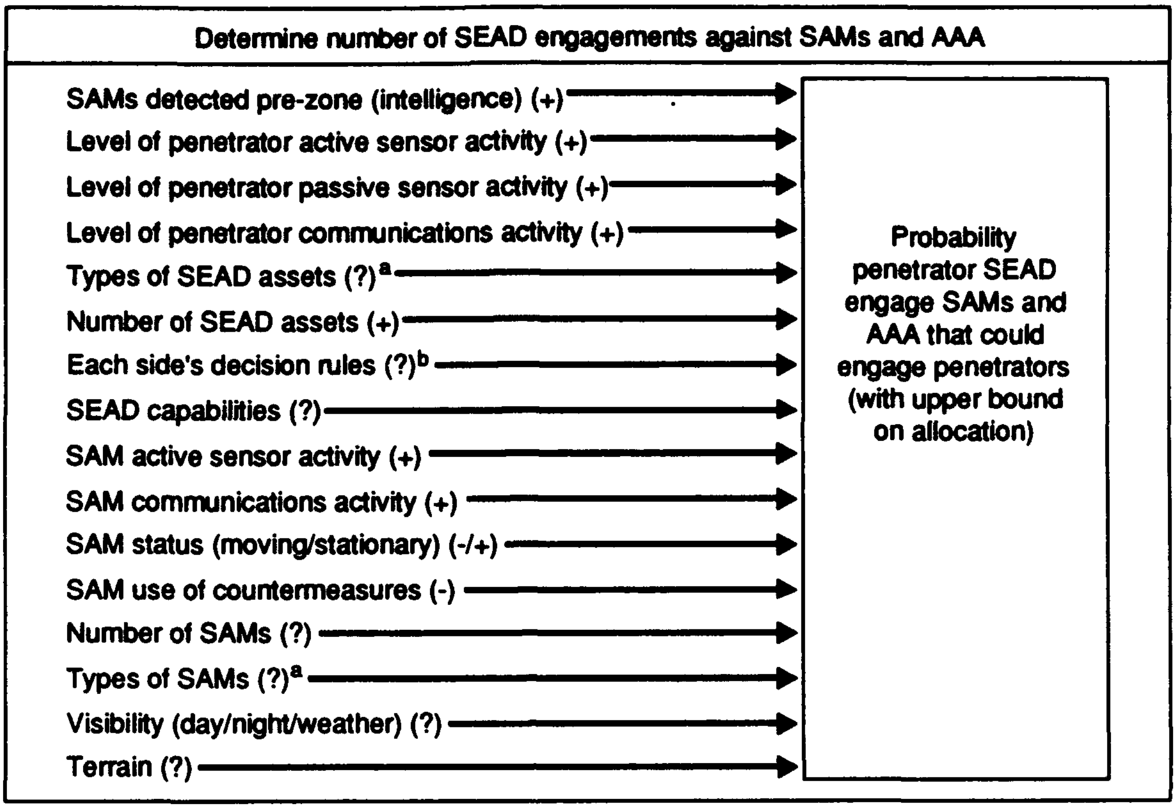
The following list of factors (see Figure 4.3) is similar to those listed above, and therefore will not require as detailed a description. However, where differences occur, they will be highlighted.

Engagements on ingress or egress. Same as above.

SAMs detected pre-zone. SAM sites that have been identified before the penetrators reach the SAM engagement zone are more likely to be engaged and destroyed or suppressed by SEAD aircraft. This factor is actually a measure of the quality of intelligence data before mission execution.

SEAD sensor jamming level and communications jamming level. These two factors are similar to the above, except focused specifically on those SEAD assets that can be used against SAM sites.

Types of SEAD assets. The types of SEAD assets will determine the effectiveness of different types of SEAD against different types of ground-based air defenses. The penetrators may have SEAD aircraft in their flight group, or standoff and ground-based SEAD may be used. Decoy assets may be used as part of a SEAD operation. Each type of SEAD asset has different advantages and disadvantages, depending upon many factors, including its delivery tactics.



[a] Includes asset types, nationality, crew training, types of munitions, sensors, decoys, and associated reliability factors for each type SEAD, SAM, or AAA asset.

[b] Includes prioritization, allocation, and decisions given the perception on each side.

Figure 4.3—Potential SEAD Engagements

Number of SEAD assets. The number of SEAD engagements tends to be driven primarily by the number of SEAD assets rather than by the number of SAM sites primarily because of the scarce supply of SEAD-capable aircraft and the availability and effectiveness of ground-based SEAD assets. The more SEAD assets available, the higher the bound on the maximum number of SEAD engagements (subject to the number of SAM and AAA sites present).

SEAD capabilities. This factor is a composite of the type of SEAD aircraft, sensors, and munitions available to perform the SEAD mission.

Each side's decision rules. Same as above.

Level of air defense radar activity. Same as above.

Level of communications among SAMs. Same as above.

SAM status (able to engage). Same as above.

SAM use of countermeasures. This factor accounts for the use of countermeasures, such as decoys and other deception activities, by SAM assets to reduce the SEAD engagement rate against them.

Number and type of SAMs and AAA. These two factors are used primarily to bound the number of SEAD engagements by type and quantity of SAMs. However, if the SEAD is being provided only by penetrating aircraft and not by standoff SEAD assets, the penetrating SEAD aircraft may be overwhelmed by the magnitude of the threat and therefore be less effective.

Visibility (day/night/weather). Visibility matters for assets that attempt to optically acquire enemy air defense assets, especially AAA assets.

Terrain. Just as terrain may matter for ground-to-air engagements, it may also matter for SEAD engagements against SAM and AAA sites.

ASSESS RESULTS OF SEAD ENGAGEMENTS AGAINST SAMS

Once the number of SEAD engagements has been determined, the actual results of the SEAD engagements may be assessed.[17] Given the number of SAM/AAA sites engaged by SEAD assets as inputs, the outputs of this section are the number of SAMs destroyed (by type, including losses to radars and to launchers), the number of SAM sites suppressed, and the number of SEAD missiles expended. Specifically, the outputs of this step include:

- Number of SAM and AAA sites destroyed (by type SAM/AAA).
- Number of SAM and AAA sites suppressed (by type SAM/AAA).
- Number of SAM and AAA engagements by destroyed or suppressed SAM and AAA assets in this assessment cycle (by type SAM/AAA).
- SEAD munitions expended.

Note that any SAM sites either engaged and not suppressed, or engaged and not destroyed, are added to the number of SAMs not engaged for the next step involving the number of SAM engagements against penetrators. In addition, SAM or AAA assets destroyed or suppressed in this assessment cycle may have fired at the

[17]The actual interactions between SEAD aircraft attacking SAM sites is very complex and difficult to understand and model. For example, the effects of lethal and nonlethal suppression are different, as are the countermeasures taken by SAM sites against each type of suppression. Although this subsection describes the basic factors that need to be accounted for in such engagements, the detailed representation to be used in TLC/NLC has not yet been decided.

penetrators before being destroyed or suppressed. These engagements need to be added to the total number of ground-to-air engagements calculated in the next step.

In addition, a fraction of the suppressed sites could be added to the number of SAM engagements, depending upon how suppression is defined in the model and the time frame involved (such as the possibility of multiple ground-to-air engagements as described above). The actual distribution of SAM losses and suppression will be based on a loss-distribution calculation after the overall number of destroyed and suppressed SAMs is calculated (See Figure 4.4).

Engagements on ingress or egress. Same as above.

Types of SEAD assets. Same as above.

Number of SEAD assets. We will want to distinguish between standoff SEAD aircraft that specialize in this type of operation, and penetrators adapted for this mission. Standoff SEAD aircraft tend to be more effective, since they face a smaller threat than penetrating SEAD aircraft. However, standoff SEAD aircraft tend not to be very effective past the first SAM engagement zone. Standoff SEAD assets also include ground-based assets used in support of SEAD missions.

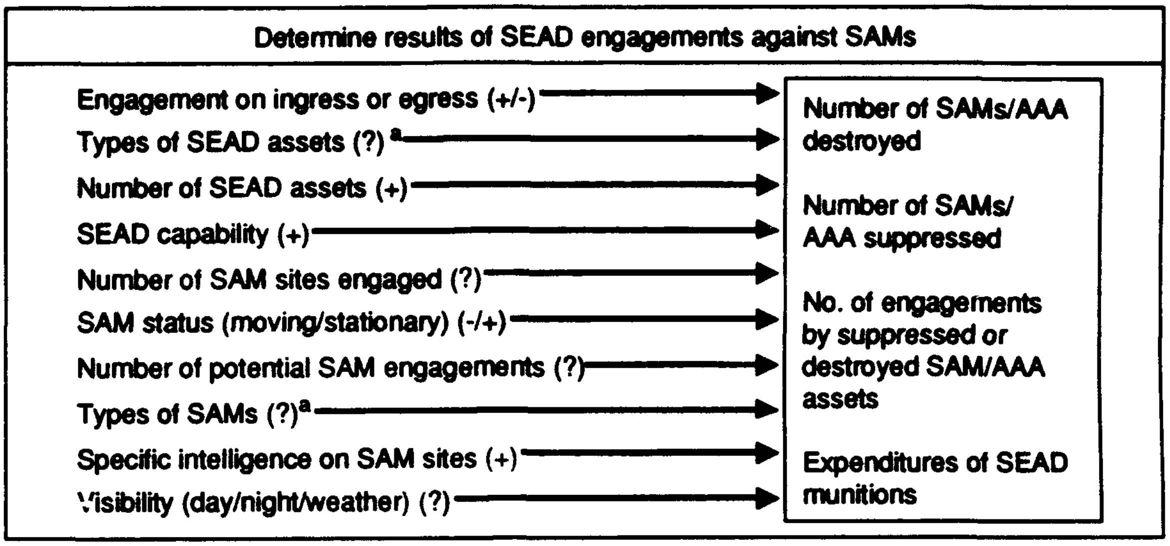
SEAD capabilities. Same as above.

Number of SAM sites engaged versus total number of SAM sites. The total number of SAM sites that can engage the penetrators determines the degree of threat against the penetrators. If this number is much higher than the number of SEAD assets, especially the penetrating SEAD aircraft, then the SEAD aircraft will tend to be overwhelmed by the SAM threat and therefore less effective.

SAM status. SAMs that are mobile tend to be harder to acquire than SAMs at fixed sites, since it is more difficult to get up-to-date intelligence and acquisition on mobile sites than on fixed sites (see below). Note that only those sites that are not currently moving and are operating may be engaged by SEAD assets this assessment cycle.

Types of SAMs. Different types of SAMs will be targeted by priority by SEAD aircraft. In addition, different types of SAMs are more or less vulnerable to SEAD operations. Decoy or dummy SAM sites should be included as a type of SAM.

Specific location intelligence information on SAM sites. One key output of the Operational Value of Intelligence and Electronic Warfare (OPVIEW) model is the distinction between intelligence that describes general target location, and intelligence that describes specific target location, and the timeliness of each.



[a] Includes asset types, nationality, crew training, types of munitions, sensors, decoys, and associated reliability factors for each type of SEAD, SAM, or AAA asset.

Figure 4.4—Assessing SEAD Engagements

The last step gave a benefit to having intelligence on the general location of different types of SAM sites. This step gives a benefit for having target location information sufficiently accurate and timely for targeting purposes. One may also wish to include the collection of BDA against destroyed or suppressed SAM sites by SEAD assets, but this is often difficult to collect without specific BDA missions assigned to this task.

Visibility (day/night/weather). Higher visibility will benefit the suppression or destruction of enemy air defenses, especially AAA sites.

ASSESS RESULTS OF SAM ENGAGEMENTS AGAINST PENETRATORS

The results of the SAM (and AAA) engagements against penetrators are simply the number of penetrators destroyed by type penetrator, the number of aircraft that abort the mission (including jettisoning their munitions), and the number of surface-to-air missiles or other munitions expended (see Figure 4.5).

Once again, a total number of aircraft destroyed and missions aborted are calculated first, while loss distribution by type of aircraft occurs as a subsequent step. One could use the defender's intelligence data about enemy penetrators as a way to increase the losses assessed against higher priority penetrators (such as killing more bombers and fewer escorts).

Determine results of SAM engagements against penetrators

Inputs	Outputs
Engagement on ingress or egress (+/-) →	Number of penetrators destroyed
Number of penetrators (?) →	
Types of penetrators (?)[a] →	Number of penetrators aborted
Number of remaining engaging SAMs (+) →	
Types of remaining engaging SAMs (?)[a] →	Expenditures of SAM and AAA munitions
Combinations of threats and countermeasures (?) →	
Visibility (day/night/weather) (?) →	

[a]Includes asset types, nationality, crew training, types of munitions, sensors, decoys, and associated reliability factors for each type of SEAD, SAM, or AAA asset.

Figure 4.5—Assessing SAM Engagements

Most of the factors have already been described above. For example, the number of engagements by SAM and AAA assets that were destroyed or suppressed by SEAD in this assessment cycle must be added to the number of engagements by SAM and AAA assets that are still functioning. Another factor to consider is that visibility will have a large effect on the ability of AAA to destroy penetrating aircraft. Although some AAA is radar controlled, higher visibility usually improves AAA accuracy.

The combinations of threats sometimes have a greater lethality against a penetrator, subject to the countermeasures employed by the penetrator. For example, the use of both a radar-guided SAM and an IR-guided SAM against the same aircraft has a better chance of killing the target. Of course, if the target aircraft employs both types of countermeasures (such as chaff and flares), this method of engagement has little advantage. (There are also tricks such as using a radar to obtain lock-on and launching a heat-seeking missile, but dual countermeasures tend to work in this case as well.) Although, the model design is not intended to explicitly represent the detailed tactics employed by each side, it is designed to address the *effects* of the use of combinations of threats and combinations of countermeasures.

5. AIR-TO-GROUND ENGAGEMENTS

Air-to-ground engagements may also be defined in a number of "rounds," but these are based on whether or not the penetrators are attacking the primary or the secondary target (see Figure 5.1). Penetrators are assumed to go after their primary target, but for a number of reasons they may not reach the primary target. For example, the visibility may be poor, or the combined air defense threat may have driven the penetrators off course. Therefore, there is a probability that the aircraft will try for the secondary target. In a similar manner, the penetrators may not be able to reach the secondary target and are forced to abort the mission.

If we assume that the probability of reaching the primary target is defined by P_1, the probability of not reaching the primary target is $1 - P_1$. If the probability of reaching the secondary target is P_2 (given the primary target is not reached), then the cumulative probability of reaching the secondary target is $P_2 * (1 - P_1)$. The probability of aborting the mission is $(1 - P_1) * (1 - P_2)$.

If the aircraft reach either the primary or secondary target, they are engaged by terminal air defenses. In addition, if the penetrators survive to attack the target, these aircraft may perform limited BDA (bomb damage assessment). This is assessed distinctly from missions flown specifically to gather BDA information unless one of the aircraft in the penetrator flight group is assigned that mission.

There are five steps to assessing air-to-ground engagements:

- Determine number of penetrators that arrive at target.
- Determine results of terminal air defense engagements.
- Determine penetrator acquisition of target.
- Assess damage against target in the model.
- Determine BDA collected by penetrator flight group.

The last step also allows for a restrike of the target if certain requirements are met. If the flight group can determine damage to the target in real time, and has unexpended weapons, it may decide to restrike the target during this mission. For example, the use of precision guided munitions with TV guidance mechanisms allowed pilots in Desert Storm to reattack a target that was not sufficiently damaged during the first attack. Conversely, an aircraft with a TV sensor may be able to

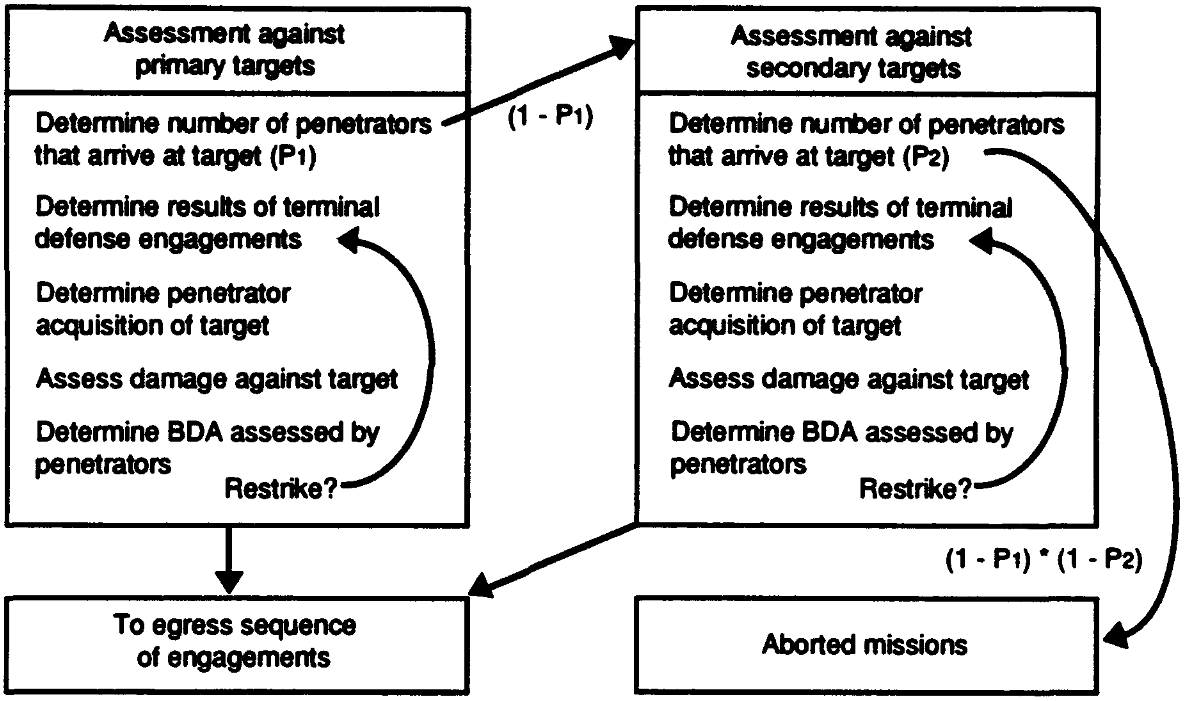


Figure 5.1—Air-to-Ground Assessment Process

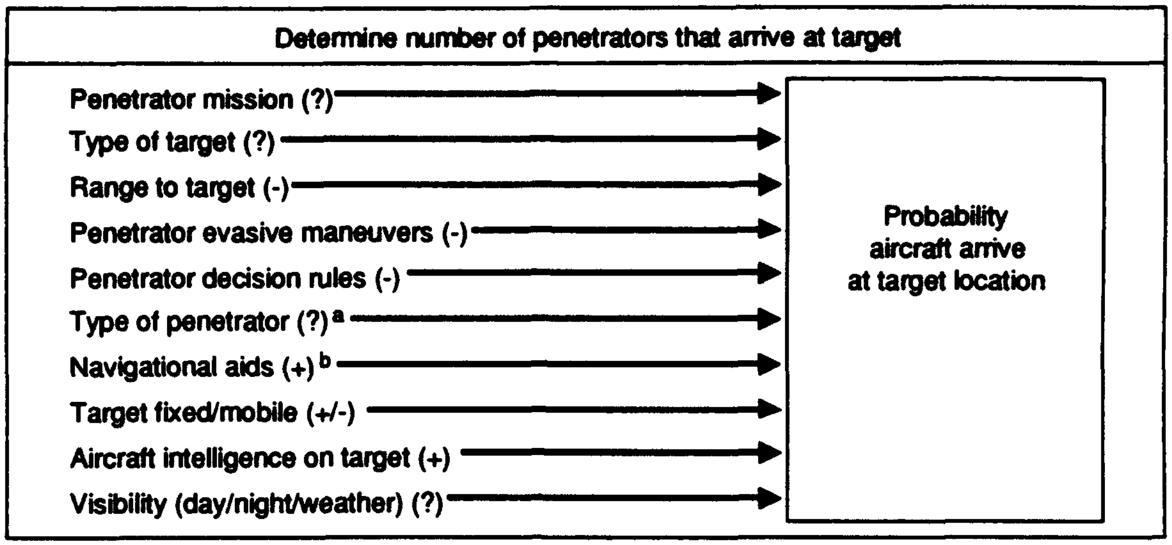
determine that the last bomb destroyed the primary target, so the remaining ordnance may be used on the secondary target. Certain advanced munitions allow for a more efficient use, rather than dropping all ordnance on the same target at the same time.

DETERMINE NUMBER OF PENETRATORS THAT ARRIVE AT TARGET

The key parameter in this step is "the probability the penetrator aircraft arrive at the target location." This parameter definition is applicable to the stochastic and deterministic versions, as well as the high- and low-resolution versions, in a similar manner to that described above. The following factors determine the number of penetrators that arrive at the target (see Figure 5.2):

Penetrator mission. The penetrator type mission (such as CAS, BAI, AI, OCA, strategic targets, etc.) will help determine whether or not the penetrator arrives successfully at the target. Some types of missions make it easier to locate the target than others.

Type of target. It has been suggested that the Air Force missions be focused on the type of target being flown against, rather than on the traditional missions



[a] Includes aircraft type, nationality, crew training, types of munitions, sensors, decoys, and associated reliability factors for each type aircraft.

[b] May include reliability of navigational aid.

Figure 5.2—Probability Penetrators Arrive at Target

listed above. To facilitate testing this concept in the model, we include the type of target in the list of factors. Decoy or dummy targets should be included as a type of target.

Range to target given mission. In addition to the type of mission, longer-range missions of a given type tend to allow more opportunity for getting lost or forced off course.

Penetrator evasive maneuvers. If a penetrating flight group has needed to perform extensive evasive maneuvers to avoid enemy threats, it may be more difficult for it to reach the primary or secondary target. The model should keep track of the number and magnitude of the threats encountered by the flight group to help determine the probability that the flight group reaches the target.

Penetrator decision rules. Given the threats listed above, the decision must be made by the flight group to proceed to the secondary target or to abort the mission. This factor could also be used to help account for targeting changes while in-flight, if feasible. An example of adaptive planning would be redirecting CAS missions that are already airborne and on-call.

Type of penetrator. Some types of aircraft are better suited for certain types of missions, and should be given that advantage. See the earlier descriptions for all of the factors included in the type of penetrator.

Navigational aids. Modern navigational aids (such as GPSS, inertial navigation devices and some infrared sensors such as LANTIRN) make it easier to find targets even after a long and threatening journey. In addition, less modern navigational aids (such as radio or radar beacons) are still effective unless suppressed or destroyed. Air combat models have not traditionally reflected the advantage of taking out the enemy's navigational beacons early in the conflict. If the enemy uses false or decoy navigational aids, this should be accounted for as well. The reliability of navigational aids should also be included.

Target fixed or mobile. If the target is fixed, the penetrators are more likely to find the target. If the target is mobile, the penetrators are more likely to find that the target has moved. However, if the area has a large number of similar mobile targets, the penetrator may choose to attack any target of the same kind (such as tanks) in the area. This aspect is handled by the "number of targets" described in the acquisition of the target step described below.

Penetrator intelligence on target location. Having seen a picture of the target area helps pilots navigate and identify the target better. Such information is useful even if using navigational aids (subject to the accuracy of the navigational aids). Once again, this level of target information is general, while in the acquisition step below it is more specific.

Visibility (day/night/weather). Adverse visibility makes it more difficult to find the target, although the ability to find the target can be improved by navigational aids as described above.

DETERMINE RESULTS OF TERMINAL AIR DEFENSE ENGAGEMENTS

The results of this step are the number of SAMs destroyed, the number of penetrators destroyed, the number of munitions expended, and the overall air defense threat faced by the penetrators at this target. Note that one could use exactly the same ground-to-air assessment steps defined above, or one could define a simplified version for terminal defenses. In either case, the input factors and output values are similar to the ground-to-air assessment, except for the value of the overall air defense threat at the target location. This last value will help determine the ability of the penetrating aircraft to acquire the target while evading the air defense

threat. If there have been recent attacks against the same target and the terminal air defenses have not yet recovered from the previous attack, this fact needs to be reflected as well.

It is important to note, however, that if the penetrators are using standoff munitions, then they may not be engaged or in any way affected by the terminal defenses. The model needs to reflect the ability of delivery beyond the range of the defenses.

DETERMINE PENETRATOR ACQUISITION OF TARGET

The key parameter in this step is "the probability that the penetrator aircraft acquires the target" (see Figure 5.3). This parameter definition is applicable to the stochastic and deterministic versions, as well as the high- and low-resolution versions, in a similar manner as described above.

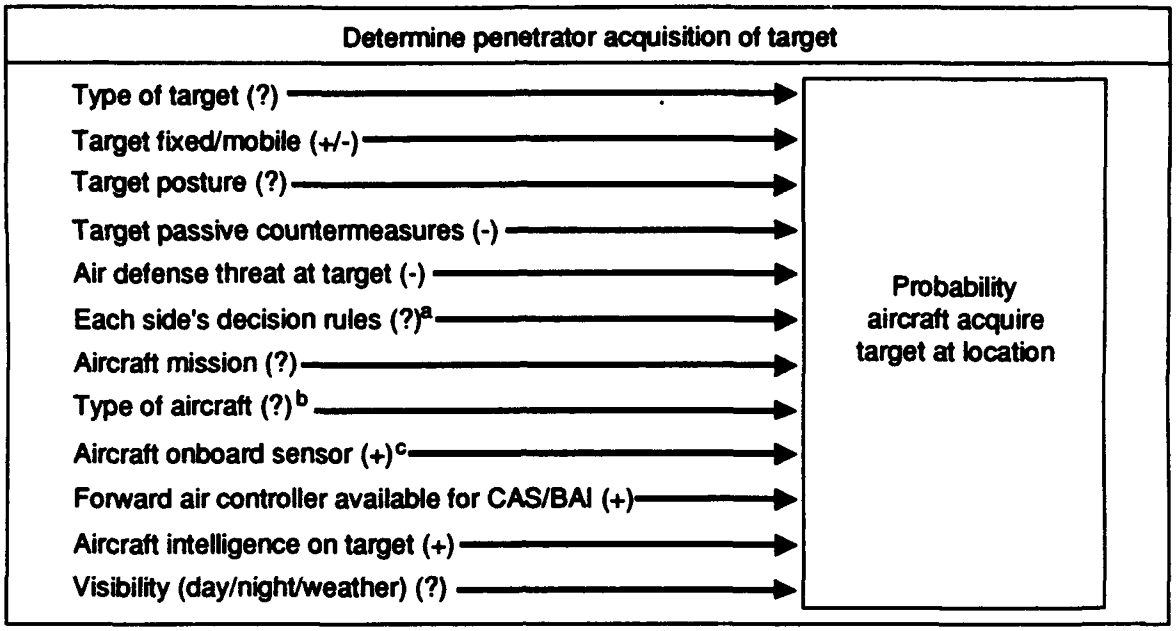
Type of target. Some types of targets are easier to acquire than others. Large fixed targets, such as airfields and nuclear power facilities, tend to be large and distinct. Other types of targets tend to be smaller and more difficult to acquire. The presence of decoy and dummy targets should be considered.

Target fixed or mobile. If this category is not included in the definition of the type of target, it should be included here. A mobile target will be harder to acquire even in the same location if it has moved locally or changed direction.

Target posture. For mobile targets, the posture of the target may matter significantly. For example, assets on a road are often easier to acquire than those off but adjacent to the road, and those dispersed in an assembly area are even harder to acquire.

Target passive countermeasures. In addition to posture, the unit may employ specific countermeasures, such as revetted positions, camouflage, dummy targets, and smoke or other obscurants.

Each side's decision rules. For the most part, this factor determines the allocation of multiple air-to-ground attacks against the many possible aim points at a target. Advanced intelligence helps this allocation process (as described below), as do advanced on-board sensors. Some of the decisions for the target include dispersing (for mobile targets) or even abandoning the target area (for both fixed and mobile targets). In addition, certain types of sensors allow for a shoot-look-shoot capability for air-to-ground attacks, thereby requiring additional allocation decision rules.



[a] Includes penetrator allocation and decision rules.

[b] Includes aircraft type, nationality, crew training, types of munitions, and associated reliability factors for each type aircraft.

[c] May include reliability of on-board sensor.

Figure 5.3—Probability That Penetrators Acquire Target

Air defense threat at the target. As mentioned above, the air defense threat at the target may make acquiring the target very difficult, as well as the delivery profile and resultant accuracy. The accuracy of delivery is better in a benign environment than in a hostile environment. The rules of engagement and delivery tactics may be strongly affected by the air defense threat at the target.

Penetrator mission and type of aircraft. Some combination of type of aircraft and type of mission will determine how good a given type of aircraft is at acquiring the target. For example, aircraft with two or more crew members may have a better chance of acquiring the target than will an aircraft with only a pilot. In addition, the delivery tactic will vary by type of aircraft, by weapon, and even by nationality.

Penetrator on-board sensors. Certain types of sensors are good at acquiring certain types of targets. In addition, certain combinations of available sensors are better at acquiring actual targets and avoiding the passive countermeasures. Some combinations of sensors may also be capable of distinguishing between live and dead targets for some types of targets. Other on-

board sensors may allow for reattacking a target given on-the-spot damage assessment.

Presence of FAC if CAS or directed BAI mission. The presence of a forward air controller can greatly enhance the effectiveness of a CAS mission or of a BAI mission directed by a ground observer. However, the FAC will be able to handle only a limited number of air-to-ground missions effectively in a specified period of time. Most models represent high CAS effectiveness because the FAC is assumed, and do not limit the effectiveness when the ability of the FAC to handle a limited quantity of aircraft is exceeded in a given time period. FACs with the ability to mark the target will speed the flow of aircraft or have aircraft wait for the next available target (subject to the air defense threat).

Penetrator detailed intelligence on target. If the penetrating aircraft have specific detailed targeting intelligence on the target, then their ability to acquire the target will be greatly enhanced, as was found during Desert Storm.

Visibility (day/night/weather). The visibility in the target area will enhance or degrade the ability to acquire the target, subject to the types of sensors being used. Good visibility may also help distinguish between a live and a dead target, although deception is possible in this area (e.g., burning oil pots on stationary tank turrets).

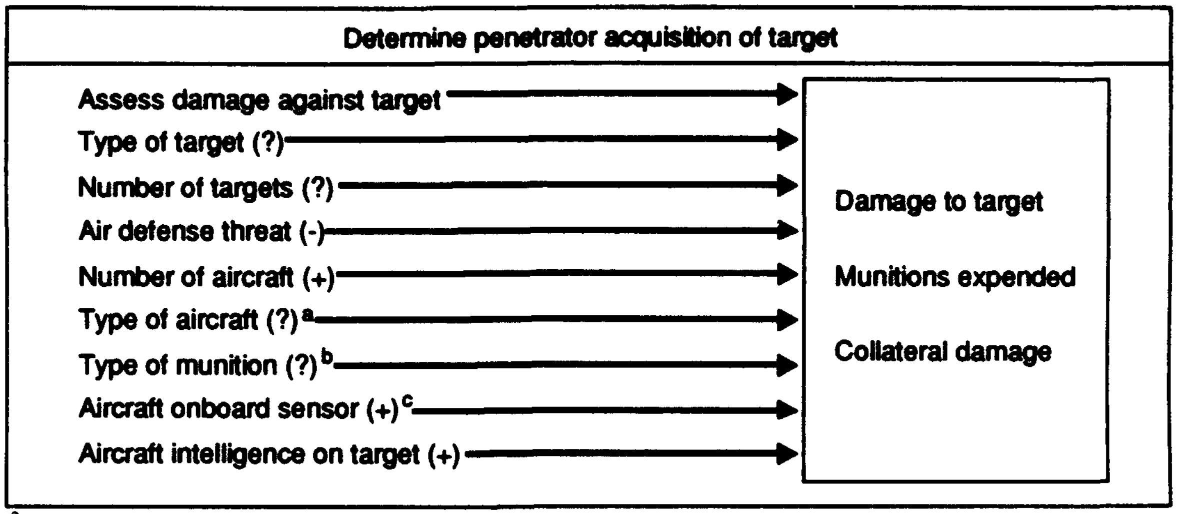
ASSESS DAMAGE AGAINST TARGET IN THE MODEL

The outputs to this step include the damage to the target, the munitions expended, and any collateral damage caused by the attack (see Figure 5.4).

Type of target. Some types of targets are more vulnerable to certain types of munitions than to others.

Number of targets. If the mission is to attack a large number of a specific type of target, then the greater the number of targets, the easier it is to hit at least some of them. (Although one must be concerned about the number of multiple hits on the same target, or no hits on some targets. In any case, the number of engagements will be bounded as a function of the number of targets and the number of shooters.) However, if one is attempting to pinpoint a single specific target, then a large number of similar targets may contribute to the wrong target being hit.

Air defense threat at the target. As mentioned above, the air defense threat at the target may make acquiring the target very difficult, as well as the delivery profile and resultant accuracy. The accuracy of delivery is better in a benign



[a] Includes aircraft type, nationality, crew training, and associated reliability factors for each type aircraft.

[b] May include weapon reliability, accuracy, and dispersion.

[c] May include on-board sensor reliability.

Figure 5.4—Assess Damage Against Target

environment than in a hostile environment.[18] However, stealth assets may face little or no threat, or standoff guided munitions may face a significantly reduced (or no) threat.

Type of penetrator aircraft and type of munition. Some combination of type of aircraft, munition, and munition delivery tactic will determine the effectiveness against this type of target. The type of munition includes the weapon's reliability, accuracy, and dispersion.

Penetrator on-board sensor. If the penetrator has an on-board sensor that allows the pilot or other crew member to guide the munition to the target (or a good fire-and-forget munition), then the damage to the target will be more effective. The reliability of the on-board sensor may also be considered.

Penetrator intelligence on the target. If there is only a single target, then this effect is already accounted for in the acquisition step above. However, if many penetrators deliver munitions against many targets, then advanced intelligence data on the target will help reduce the number of multiple kills in a single mission, as was

[18]The accuracy as a function of the air defense threat may also be related to crew experience, as mentioned in type of aircraft above.

found during Operation Desert Storm. Good BDA will also help reduce the number of multiple kills of the same target across several missions.

DETERMINE BDA COLLECTED BY PENETRATOR FLIGHT GROUP

The outputs of this step are to determine the observed damage to the target and any collateral damage as collected by the penetrating flight group or pilot report (see Figure 5.5). It is assumed that if there are certain types of aircraft equipped for BDA, or certain types of sensors and munitions that enhance BDA (such as TV-guided bombs), then BDA will be enhanced. Note that this assessment is distinct from specific BDA missions flown separately from a penetrating mission against this target.

Type of target. Different types of targets have different BDA requirements. In this case, we assume that whether the target is fixed or mobile is included in the type of target. Secondary explosions, however, will tend to enhance BDA as a function of the type of target. Damage to decoy or dummy targets should also be considered at this point.

Number of targets. Obtaining some BDA reports is easier given a large number of targets. However, getting BDA on all targets is more difficult if there is a large number of targets.

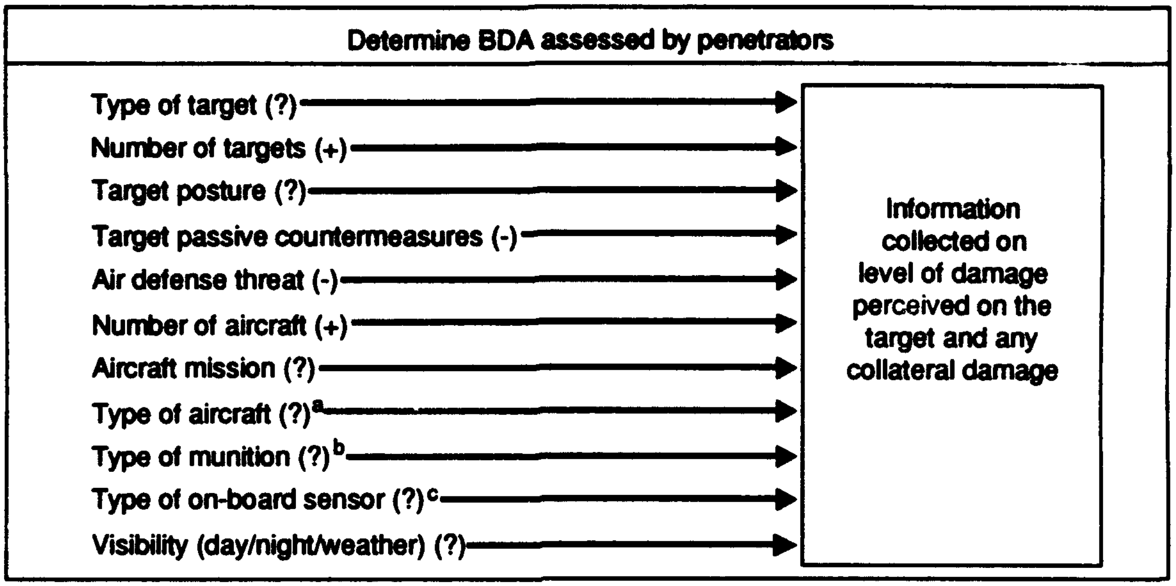
Target posture. BDA is more difficult if the target is dispersed in terrain with limited visibility.

Target passive countermeasures. Many passive countermeasures, such as camouflage, will be blown away by the blast and therefore will not affect BDA. Other types of passive countermeasures, such as revetments, decoys, and smoke, will make BDA more difficult.

Air defense threat. Just as it is more difficult to acquire a target in a high air defense threat, BDA is equally difficult under the same conditions.

Penetrator mission, type of aircraft, type of munition, and type of sensor. Some combination of these factors will help determine how well one could assess BDA against the target. For example, a TV-guided bomb from an F-111 will provide fairly good BDA, and an aircraft equipped to perform BDA, such as an RF-4, will better perform the mission.

Visibility (day/night/weather). The visibility in the target area will enhance or degrade the ability to perform the BDA mission, subject to the types of sensors being used.



[a] Includes aircraft type, nationality, crew training, and associated reliability factors for each type aircraft.

[b] May include weapon reliability, accuracy, and dispersion.

[c] May include on-board sensor reliability.

Figure 5.5—Collect BDA on Target

6. SOME FINAL NOTES ON THE HIGH-LEVEL DESIGN

This high-level design document presents the design of a family of air combat models that can be deterministic, stochastic, high-resolution, or low-resolution. In addition, we wanted to account for factors not traditionally addressed in air combat models, such as navigational aids, the value of intelligence against a target and against the threats to penetrators, the value of BDA collection (including timeliness), the value of disrupting enemy command and control of air defense assets, and the advantages of stealth tactics as well as technology. All of these factors influence the decisions made by each side during a conflict and their command, control, and communications systems. These factors will be addressed in more detail in subsequent documents. This document only addressed the need for allocation decisions at specific points in the assessment processes.[19]

In addition, the model design will eventually include specific representations of fratricide as a function of the degree of uncertainty in a given situation. For example, if there is a high penetrator threat, high level of radar and communications jamming, and returning friendly aircraft, then the odds of fratricide are significantly higher than in a more benign environment.

One feature that may not be apparent is the emphasis on "outputs first." This approach to variable resolution modeling was originally applied to the S-Land model in the RSAS (Allen and Wilson, 1987). In this approach, the outputs of a given assessment process are defined first, and then the factors necessary to calculate that output are defined second. The process of calculating the outputs may become more elaborate as user needs and data availability increase. This approach is key to successful variable resolution modeling.

This approach is also essential for the goal of calibrating this model to the outputs of higher-resolution models. What has been addressed for the most part of this design have been how many aircraft and/or SAMs of each type destroy each other in a given engagement assessment process. Although the factors contributing to the

[19]One important point in C3I modeling is that unless the model's assessment processes reflect a difference in outcome for different decisions, rules of engagement, and tactics, the model will not be able to measure any benefit to good or bad information, plans, or decisions. That is why this document focused on the assessment processes rather than on the decision processes, so that the effects of different types of decisions will have an effect in the model's assessment processes.

actual assessment have been specified, the definition of the assessment process itself has not been defined in too much detail. This lack of detail is intentional, and will allow us to calibrate this air combat assessment model to higher-resolution air combat models, such as Tac Brawler, RJARS, and other higher resolution models. The exact calibration process is reserved for the next phase of this documentation.

Appendix
GEOMETRIC CALCULATIONS FOR ENGAGEMENT ASSESSMENT

In the TLC/NLC air model, a number of geometric calculations need to be performed to ensure that the assessment process adequately addresses range and altitude considerations. For example, the range at which a radar may detect a given penetrating aircraft depends on a variety of factors, but the model must know when to *check* to see whether or not a given type of penetrator may be detected by a given type of radar. Without some predefined time or event, the model could be faced with a large combinatorial problem of checking every combination of sensor and penetrator every small time step. As an alternative, the multiple network structure of TLC/NLC lends itself to some automatic calculation points so that the potential engagements may be efficiently calculated. (Such detailed calculations are necessary only in a detailed model that represents flight paths, rather than in one with less detail that simply assumes the flight paths, as in the RSAS model.)

Four geometric calculations are associated with a flight group flight path described in this appendix:

- Automatically generated detection bands and nodes.
- Determining the number of engagements in a zone.
- Calculating air-to-air engagement assessment points.
- Calculating "corridor" regions.

AUTOMATICALLY GENERATED DETECTION BANDS AND NODES

In most cases, the detection range of a given sensor exceeds the engagement range of the weapon systems that depend upon those sensors. For example, the detection range of radar exceeds the engagement range of most surface-to-air missiles. In addition, the information available to the radar is often a function of the range to the target aircraft.

For example, one may be able to determine at long range that aircraft are flying at a given range, bearing, and altitude, but at a closer range can determine the number of aircraft, and at very close range, even some of the features to distinguish certain types of aircraft from others. Each level of information can be considered "degrees of detection," similar to those applied in the OPVIEW model. The least

degree of detection lets the observer know that something is there, but little more than the magnitude of the signal. In the event of extreme jamming, this may be all of the information one receives before the aircraft reach an engagement range.

At the next degree of detection, the number of penetrating aircraft may be distinguished, thereby allowing the command controlling the defenders more information with which to allocate its resources. At the closest degree of detection, the types of aircraft in the flight group might be distinguishable, thereby allowing even more information to the defending command to better allocate its resources against the penetrating threat.

To efficiently implement these degrees of detection in the model, we can automatically generate additional network nodes to determine when (or if) the penetrating aircraft were detected. For example, the SAM and CAP engagement zones are assumed to have a specified number and type of sensors (e.g., ground-based or airborne radars and other sensors). These sensors have some maximum detection range, depending upon a reasonable aircraft radar cross-section. A detection node may be placed on the flight path as a good place to test for when or if the penetrating aircraft will be detected to a specified degree along that flight path. If the number of sensors is reduced or suppressed to be ineffective, the automatically generated nodes associated with these detections can be deactivated.

As shown in Figure A.1 (which is a copy of Figure 2.2), the detection ranges place two or more nodes on the flight path of our sample penetrator mission. At the farthest range, the model will test for when (or if) the penetrators are detected. This range will be a function of the number and type of radars in the engagement zone, and the aircraft type in the model with the largest radar cross-section. If the flight group contains only aircraft with smaller radar cross-sections, then the location (or time) of the actual detection may be calculated for that combination of radars and aircraft. Note that the number of aircraft, the degree of penetrator radar and communications activity, and the degree of penetrator jamming activity against radar and communications will all contribute to this detection range. Of course, extreme radar jamming will obviously alert the defenders that something is up, but the magnitude of the raid and the exact location, number, or types of penetrators may be adequately disguised by the jamming activity.

At the next level of detection, the test may be made for whether or not the number of penetrators may be determined. As an alternative, this test may be performed at the same time as the first test for detection. One must be careful,

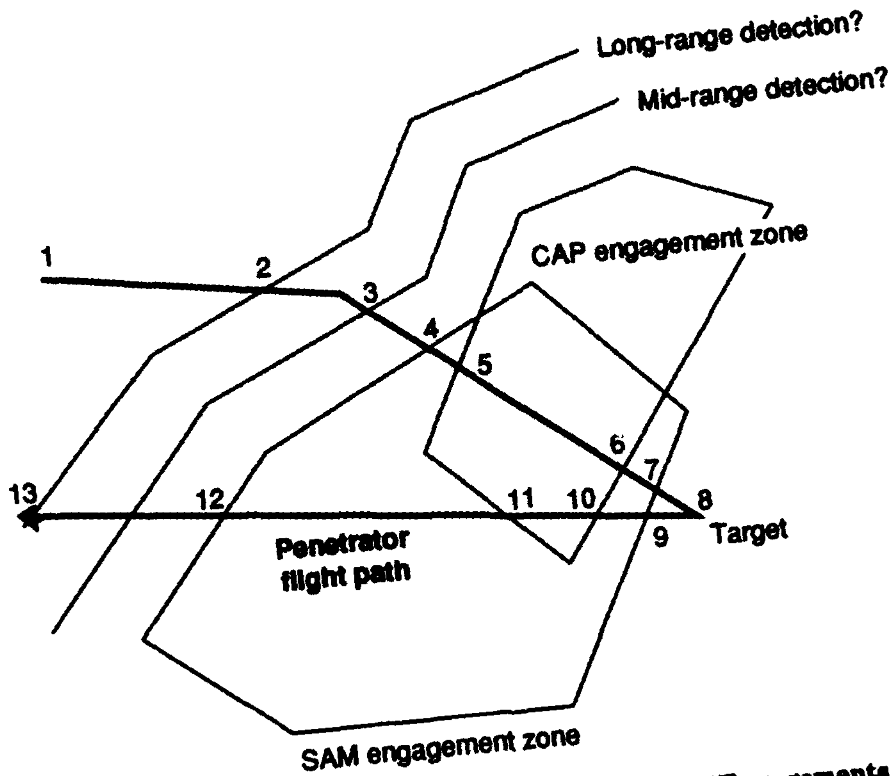


Figure A.1—Example of Determining Sequence of Engagements

however, that if the airbase from which the penetrators took off is within the detection ranges, the tests must still be performed, even though the detection test node does not lie on the flight path.

Finally, the test for whether or not the types of penetrating aircraft can be distinguished is made. All of the preceding caveats apply to this test as well.

For the current TLC/NLC model implementation, one simplifying assumption has been made regarding the detection zones. The assumption is that each detection zone is associated with a single engagement zone for ease of calculation. The model user must ensure that this assumption is correct for the scenarios being examined.

DETERMINING THE NUMBER OF ENGAGEMENTS IN A ZONE

One of the most important calculations is the number of engagements that can be made by SAM sites or interceptors. However, it is inefficient to make this calculation from every SAM site or CAP station in the engagement zone. Instead, one can make this calculation from the flight path, since we are assuming that the

SAM sites and CAP stations are "uniformly" distributed in the engagement zone.[20] Sample calculations are given below:

1. Given each type of SAM in the SAM engagement zone, and the cross-section of each type of aircraft in the flight group, read from a look-up table the maximum engagement range (the range required for lock-on).
2. Determine the horizontal component of the range by removing the altitude component from the absolute distance (i.e., distance squared minus altitude squared is horizontal range squared).
3. If the altitude is less than a specified minimum, determine the range at which the line of sight is sufficiently long that the SAM can engage the penetrators. If the altitude is sufficiently high, the SAMs may actually achieve an engagement rate of greater than one engagement per penetrator flight group, thereby creating a "shoot-look-shoot" engagement.
4. The resulting horizontal range is used as the width to each side of the flight path in which SAMs of that type can engage the penetrators of the type specified (see Figure A.2).
5. Take the ratio of the area of the flight path times the width divided by the SAM engagement area. Since the SAMs are assumed to be uniformly distributed, the area covered by the flight path and width is an approximation of the maximum number of SAM engagements that can occur.

The previous calculations determine only the maximum number of engagements that could occur given no penetrator countermeasures. This base calculation is necessary so that the analyst may use the model to measure the effects of the countermeasures on their ability to reduce the number of SAM engagements. For example, if no countermeasures means that 100 SAMs can engage the penetrators in this zone, and the countermeasures reduce the number of

[20]The design also assumes that given a specific combination of type of aircraft, and type of SAM or AAA, the probability of kill given an engagement is a constant modified by the geometry factor. Therefore, the representation of the effect of offset distance on probability of kill must be included in the geometry factor.

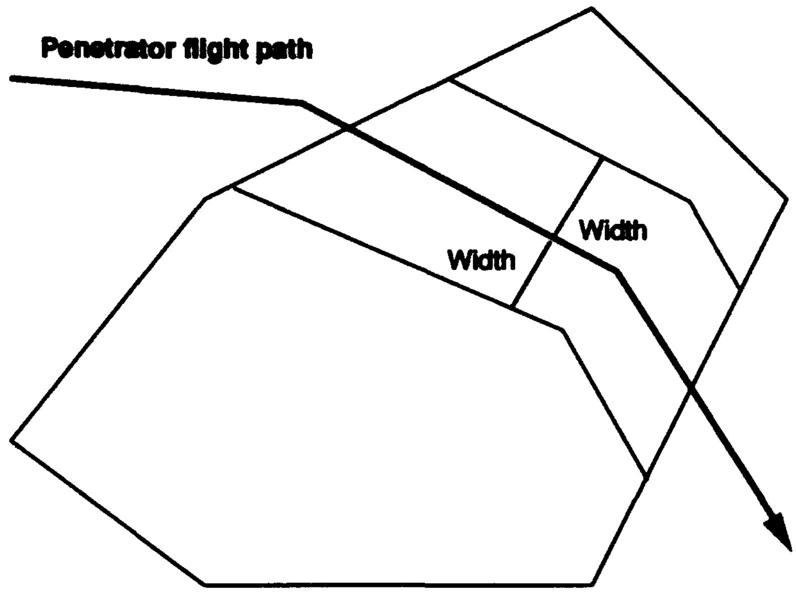


Figure A.2—Calculating Area of Engagement

engagements to 30, then the countermeasures reduced the possible SAM engagements 70 percent.

A similar type of calculation can be made for the number of air-to-air engagements possible in a CAP zone.

CALCULATING AIR-TO-AIR ENGAGEMENT ASSESSMENT POINTS

One option for making some of the geometric calculations more efficient is to calculate an air-to-air engagement point within the air-to-air engagement zone. It is hoped that these engagement points can be pre-processed before model execution, although one may wish to dynamically calculate the engagement points.

Assuming the engagement points are preprocessed, this calculation can be performed in a number of ways. One may simply assume that the air-to-air engagements occur at the center of the line segment formed by where the flight path enters the zone and where it exits (accounting for any turning points en route).

As an alternative, one could calculate on ingress a CAP engagement point closer to the entry point, and a strip alert engagement point closer to the exit point. For egress, it is less likely that strip-alert aircraft will be able to engage the

penetrators, subject to where the interceptor air base is with respect to the flight path.

The air defender's aircraft allocation procedure may also wish to specify whether it prefers to engage en masse or more sequentially in an effort to draw off any escorts. The "doctrinal" or "air campaign plan" parameters could be specified before the run to determine which allocation procedure is preferred when pre-processing the air-to-air engagement zones.

The number of turning points in the penetrator's flight path may affect the timing and location of the interceptor's engagement point. Although this may be below the level of resolution in the model, we will need to account for the effect of turning points in possibly reducing the air-to-air engagement probability.

CALCULATING "CORRIDOR" REGIONS

One aspect that is often overlooked in lower-resolution air combat models is the penetrators' ability to punch a corridor in the enemy air defenses and continue to push aircraft through that hole against reduced enemy air defenses. If the SAM engagement zones are large, and if the SAMs are assumed to be uniformly distributed, then the number of SAMs that needs to be suppressed in the model is significantly greater than would be the case in reality.

For example, if there are 1000 SAMs in the SAM engagement zone, and only 100 SAMs in the corridor, then the penetrators have to suppress only 100 SAMs to ensure relatively safe passage through the corridor. In reality, the defender may be able to move mobile SAMs into the suppressed zone, but this will take time while additional raids continue to penetrate. In the model, however, the following raid will engage 10 percent of the 900 uniformly distributed SAMs in the engagement zone, or 90 SAM engagements—this is in spite of the fact that all of the SAMs originally in the corridor were destroyed or suppressed.

To adequately account for the effects of creating a corridor in the air defenses, we propose creating a "corridor" region. The corridor region would be automatically pre-processed around the flight paths in the model to separate SAM engagement zones into areas that are likely to be suppressed and areas less likely to be suppressed. If the SAM regions are small, some of them will be completely encompassed by the corridor. If the engagement zones are large, then they will likely be divided into sub-zones within and without the corridor (see Figure A.3). Air defense assets would be redistributed in the engagement zones as a function of

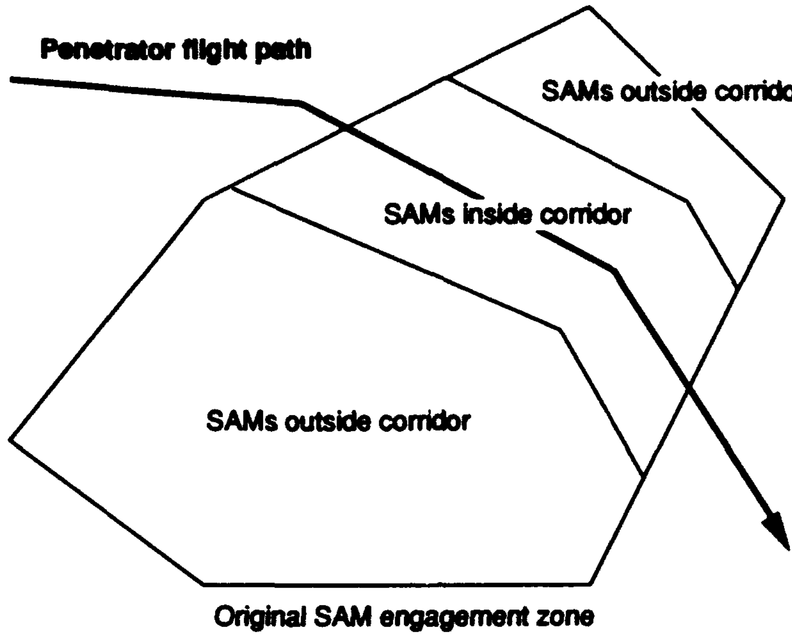


Figure A.3—Corridor Zones

time, and therefore the definition of the corridors will need to be examined over time. A similar calculation of such corridors can also be created for "sweep" missions attempting to clear enemy CAP from the flight path of following penetrators.

As an alternative to creating corridors, one could require that SAM and AAA engagement zones be small rather than large, thereby precluding the need to calculate corridors. This does create a tradeoff, however, in the number of SAM and AAA zones that the user needs to define.

BIBLIOGRAPHY

Allen, Patrick D., "Combining Deterministic and Stochastic Elements in Variable Resolution Models," in Paul K. Davis and Richard Hillestad (eds.), *Proceedings of Conference on Variable-Resolution Modeling, Washington, DC, 5-6 May 1992,* RAND, CF-103-DARPA, 1992.

Allen, Patrick D., and Barry A. Wilson, *The Secondary Land Theater Model*, RAND, N-2625-NA, July 1987.

Cesar, E., P. Allen, and R. Eden, *Finding a New Approach to Measure the Operational Value of Intelligence for Military Operations: Annotated Briefing*, RAND, N-3551-A, 1992.

Davis, Paul K., and H. Edward Hall, *Overview of System Software in the RAND Strategy Assessment System*, RAND, N-2755-NA, December 1988.

Hillestad, Richard J., Reiner Huber, and Milton G. Weiner (eds.), *New Issues and Tools for Future Military Analysis: A Workshop Summary*, RAND, N-3403-DARPA/AF/A, 1992.

Hillestad, Richard, Louis Moore, Eric Larson, *Theater-Level Campaign Model; Nonlinear Tool Kit: An Overview*, RAND, MR-180-AF/A, forthcoming.

McDonough, L., S. Bailey, A. Koehler, *MAPVIEW User's Guide*, RAND, MR-160-AF/A, forthcoming.

Moore, Louis, *CADEM: Calibrated Differential Equation Methodology for Aggregate Attrition*, RAND, MR-170-AF, forthcoming.

Sollfrey, William, *RJARS: RAND's Version of the Jamming and Aircraft Radar Simulation*, RAND, N-2727-1-AF/A/DARPA/DR&E, 1991.

Sollfrey, William, *RJARS: RAND's Version of the Jamming and Aircraft Radar Simulation: Developments in 1991*, RAND, N-2727-1/1-AF/PA&E/OSD, 1992.

Tac Brawler Air Combat Simulation User Manual Rev 5.0, DSA Report #908, Decision Science Application, June 1988.

TAC Thunder Analyst's Manual Version 4.6, CACI Products Company, Arlington, Virginia, November 1989.